WEST FALMOUTH HARBOR RESTORATION FEASIBILITY STUDY

Final Report

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BUREAU OF WATER RESOURCES

AND

U.S. ENVIRONMENTAL PROTECTION AGENCY

REGION 1

This project has been financed partially with Federal Funds from the U.S. Environmental Protection Agency (EPA) to the Massachusetts Department of Environmental Protection (MADEP) under Section 604(b) of the Clean Water Act. The contents do not necessarily reflect the views and policies of EPA or of MADEP, nor does the mention of trade names or commercial products constitute endorsement or recommendation for use.

Table of Contents

List of Tables

List of Figures

Executive Summary

This report provides information on the current (pre-project) biological and physical condition of three sub-embayments of West Falmouth Harbor, Massachusetts, whose tidal exchanges are impacted by tidal restrictions (culverts) under roads. The data provided in these reports were used to predict how removal of tidal restrictions might change hydrodynamics in the sub-embayments and potentially impact biological and cultural resources. Biological data collected include quantitative data of marsh plant communities, their distributions, and stresses. Physical data consists of the current tidal hydrodynamics of sub-embayments relative to tidal fluctuations in West Falmouth Harbor and elevations of infrastructure and natural communities that might be impacted by restoring tidal exchange.

The three tidal restrictions include: (1) Little Neck Bay, restricted by a culvert under Chapaquoit Road, (2) Shrub Bog, restricted by the Chapaquoit Road culvert and a culvert under Little Neck Bars road, and (3) Oyster Pond, restricted by a culvert under the Shining Sea bike trail.

Tidal fluctuations in Shrub Bog are dependent on tidal hydrodynamics of Little Neck Bay. Because Shrub Bog is a speciose freshwater ecosystem, it was concluded that it would be better to continue to restrict tidal flow to it and, if tidal exchange to Little Neck Bay is restored, install a flap gate to prevent saline water from entering it. However, since both Chapaquoit Road and Little Neck Bars Road (which is lower) will both be inundated during a 4-y storm event, Shrub Bog is bound to receive saline water in the near future. When this happens, much of the freshwater vegetation will be impacted.

Little Neck Bay is also a severely-restricted embayment. However, restoring complete tidal exchange to it would cause Little Neck Bars Road to be overtopped during minor storms. The only way to avoid frequent overtopping would be to raise the elevation of the roadbed by three feet and/or install a tide gate on the culvert under Chapaquoit Road that could be closed during major storms. Alternatively, a slightly larger and lower culvert could be installed that provides partial tidal restoration. This could prevent overtopping of the road flood during intermediate-intensity events. This option would be a cheaper alternative and not require intensive management to prevent flooding of the road. It would also increase the intertidal area of Little Neck Bay by a factor of five, increase the tidal prism by a factor of eight, and decrease the residence time from six days to less than one day. Restoring partial tidal exchange should improve marsh and benthic habitat, but not completely restore it. The Town of Falmouth will have to determine the costs versus benefits of the two alternatives and determine whether the culvert would be a safety hazard.

Tidal exchange to the Oyster Pond could be achieved by lowering the restrictive shoal upstream and replacing the present 3-ft diameter culvert with a 4 X 4-ft box culvert. This would increase tidal range and tidal prism by a factor of 2.5 and double the rate of flow through the culvert. It would also make the culvert safer than the present one. Increasing the turnover time should improve marsh and intertidal habitat and improve marsh health.

Acknowledgements

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1. INTRODUCTION

The coastline of Cape Cod is rich in small estuaries, embayments, and tidal creeks. Almost all of these geomorphic landforms are bordered by salt marshes at the upland/wetland ecotone. These salt marshes are important to the economic, cultural, and environmental health of the Cape because they help maintain estuarine water quality, provide critical habitat for estuarine-dependent species, and export dissolved and particulate organic carbon to bays and sounds, that in turn, support estuarine food webs critical to commercial and recreational fisheries. Prior to wetland protection regulations of the Clean Water Act and the Massachusetts Wetland Protection Act, salt marshes on the Cape were replaced or degraded by human infrastructure. In some cases, spoil was placed on marshes to provide bedding for roads crossing wetlands and tidal creeks. The road crossings restrict tidal exchange between the creeks and connecting embayments, affecting water surface elevation, flood volume, salinity, sediment transport rates, and the movement of aquatic organisms (Mac Broom et al. 2010).

The Cape Cod Commission (2012) reported that "approximately 85% of the wastewater flow into Cape Cod's embayments comes from on-site septic systems." Nitrogen, the most problematic nutrient in wastewater, has led to the eutrophication of many embayments and their wetlands, particularly on the upstream side of the tidal restrictions. This eutrophication has lead to poor water quality and clarity, loss of marsh and seagrass habitat, and a reduction in fishery resources. Although salt marshes can assimilate excess nitrogen in tissues (Hopkinson and Schubauer 1984) and microbial denitrification in marsh sediments is well-documented (Kaplan et al. 1977), large concentrations of nitrogen causes marsh plants to allocate more biomass to aboveground leaves and less to roots, eventually leading to the physical deterioration of marshes and a reduction in functioning (Deegan et al. 2012).

In recent years, the Commonwealth of Massachusetts and citizens of towns throughout the Cape have decided that restoration of tidal flow to salt marshes and embayments should be undertaken, where practical, to reverse some of the degradations to coastal estuaries due to restrictive culverts. In consultation with the Massachusetts Department of Environmental Protection (MADEP), Massachusetts Division of Ecological Restoration, and the Town of Falmouth, three embayments in West Falmouth Harbor were identified as having potential for restoration by retrofitting existing culverts with less restrictive ones (Figure 1.1). This report, funded by the MADEP Section 604b Program grant, examines the feasibility of restoring tidal flow to these tidally-restricted embayments. It provides information on physical impairments to tidal flow, the current ecolological condition of the restricted embayments and their associated wetlands, and the infrastructure and resources that could be potentially impacted by alleviating the tidal restrictions relative to several culvert replacement scenarios.

Other products will be provided in an appendix and as digital files, including the QAPP, a hydraulic modeling report provided by the Woods Hole Group, a photographic archive of key locations in the study, an excel file of all tables, geospatial coordinates and elevation data for infrastructure and benchmarks, data on cross-sections of creeks and ditches, raw and corrected RTK data, list of abutters, a PowerPoint file of all figures used in the report, and a digital copy of this report.

2. APPROACH

2.1 Location

Three tidally restricted embayments associated with West Falmouth Harbor in Falmouth, Massachusetts, were studied to determine the feasibility of restoring a more natural tidal regime to them (Figure 2.1): (1) Oyster Pond embayment, which is separated from Harbor Head, and hence West Falmouth Harbor, by a restrictive culvert under the Shining Sea bike trail, (2) an unnamed embayment, herein called Little Neck Bay, which is separated from West Falmouth Harbor by a restrictive culvert under Chapaquoit Road, and (3) an unnamed embayment, herein called Shrub Bog, which is separated from the Little Neck Bay by a restrictive culvert under Little Neck Bars Road.

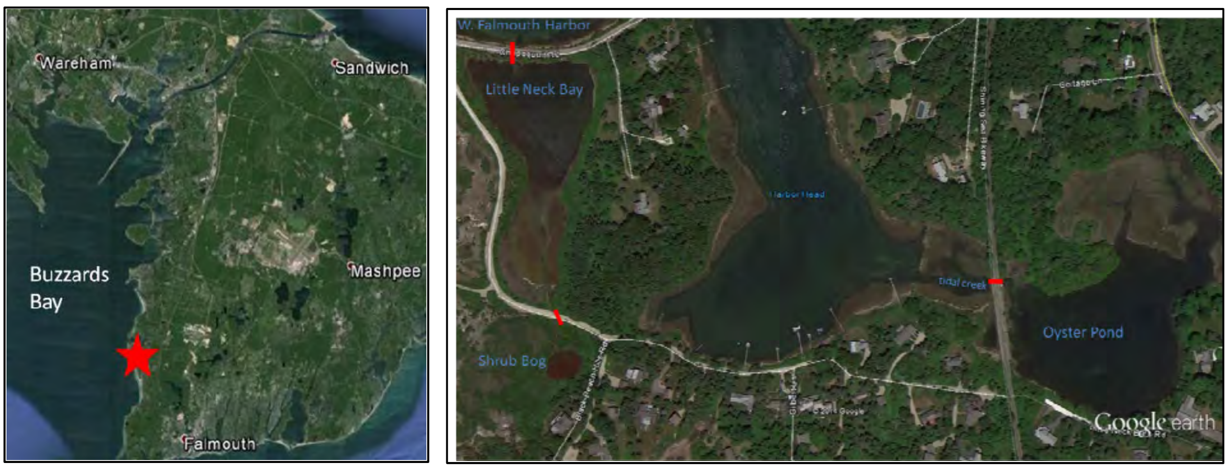

Figure 2.1. Three embayments separated from West Falmouth Harbor by restrictive culverts. The red star shows the location of study area in relation to Buzzards Bay. Culvert locations are indicated by red lines.

2.2 Geomorphic surveys

A real-time-kinematic (RTK) GPS survey was conducted of relevant landscape features, artificial tidal restrictions (culvert inverts and obverts), natural tidal restrictions, important geomorphic and landscape features (elevation of vegetation types and ecotones, creek and ditch cross-sections, embayment depths), and infrastructure (roads, house foundations, etc.) that could potentially be affected by flooding after culvert replacements. Several benchmarks (BM) were also established in the course of the RTK survey to facilitate possible future survey efforts. In addition, Lidar imagery was obtained to help determine where the lowest-lying properties and infrastructure occur.

All the studied embayments have maintained mosquito ditches in them and so RTK data were acquired to determine the cross-section morphology of ditches by measuring from top-of-bank to thalweg to top-of-bank on the opposite sides. In addition, three cross-sections (X-S) were measured across the tidal creek draining Oyster Pond in order to understand potential drainage effects associated with its channel morphology: one downstream X-S at a natural constriction before the creek empties into Harbor Head, one about 50 ft upstream from the constriction, and another about 80 ft even further upstream.

2.3 Data loggers

Pressure transducer data loggers (Onset, Inc.) were placed in embayments on both the upstream and downstream sides of studied culverts to record changes over time in water height above the transducers. The loggers were usually installed about 25-50 ft from the culverts to insure that they would be placed at a sufficient depth to always be covered with water during all or most of the period of measurement. However, the upstream data logger for Little Neck Bay also functioned as the downstream logger for Shrub Bog. Although this logger was located about 830 ft from the Little Neck Bars Road culvert, it was reasonably assumed that this logger would adequately measure water level fluctuations in the entire embayment. A data logger was also placed in the Shrub Bog that only recorded atmoshpheric pressure, i.e., it was never under water, so that changes in atmospheric pressure could be subtracted from water level readings to compensate for changes in atmospheric pressure over time.

Loggers were left in the embayments for entire monthly tidal cycle (06/4/14 to 07/22/14), which incorporated two Spring tides (effects of a full and a new moon) and two Neap tides (effects of two quarter moons). Data were graphed using HOBOware Pro software Version 3.7.1 (Onset, Inc.) to compare embayment water-level fluctuations to the tidal fluctuations in West Falmouth Harbor proper. Summary hydrologic statistics were also calculated for the period of record.

The monthly data could be tied to the Chappaquoit Point, long-term NOAA data (Station ID: 8447685) to model longer-term hydraulic fluctuations and storm surge based on past responses to reductions in atmospheric pressure associated with low-pressure storm systems. The predictive data could also be used to model various culvert replacement scenarios, i.e., relative to various culvert sizes. The subcontracted modeling effort used these data to model potential hydrologic fluctuations relative to various culvert replacement scenarios. The modeling report is provided in the Appendix.

2.4 Vegetation

The spatial distribution of vegetation cover types was estimated by manually drawing boundaries in the field on aerial photos and transferring these digitally to maps. This spatial distribution provides a baseline by which to compare changes in cover types after culvert enlargements have been completed, bearing in mind that it might take several years for vegetation changes to fully take place after tidal exchange is improved.

Coverage of plants, by species, were estimated for all embayments within a series a 1-m^2 sample plots in each of the identified cover types. Coverage was determined by first determining one of nine coverage catergories the species represented and then assigning the midpoint of the category to the species. The categories and midpoints (in parentheses) were T (trace, < 1%), 0-5.0 (2.5), 5-25 (15), 25-50 (37.5), 50 (50), 50-75 (62.5), 75-95 (85), 95-100 (97.5), and 100 (100).

2.5 Additional miscellaneous information.

Information on property owners abutting the embayments was compiled, including names, addresses, and parcel information. Observations were made on culvert condition, condition of vegetation, embayment morphology, infrastructure, and anything else that might be pertinent to the removal of culverts.

3. RESULTS

3.1 Little Neck Bay

3.1.1 Location. Little Neck Bay is located on the south side of Chapaquoit Road, about 730 ft west of Harbor Head (Figure 3.1). The bay is upstream from a restrictive culvert under Chapaquoit Road that hydraulically connects Little Neck Bay to West Falmouth Harbor. The culvert under this road is 1.0 ft in diameter on the downstream side, flared to 2.0 ft diameter on the upstream side, and is approximately 38 ft in length (Table 3.1). The culvert is beginning to deteriorate and is heavily shoaled on the upstream side, where several inches of sediment have accumulated. Further, the downstream side of the culvert is exposed during low tides in West Falmouth Harbor, thus restricting fish passage about 36% of a typical lunar tidal cycle (Figure 3.2).

A dirt road, Little Neck Bars Road, traverses the western and southern end of Little Neck Bay. RTK[1] data were collected for points along this road, along Chapaquoit Road, on the marsh surface, to determine cross-sections of ditches, and at the base of lowest-lying infrastructure on the eight private properties abutting Little Neck Bay, five of which occur south and east of Little Neck Bars Road (Figure 3.2). Elevations of important man-made and natural features are provided in Table 3.2. Raw RTK data, including local benchmarks, and the names and contact information for abutters is provided in the digital file accompanying this study.

3.1.2 Water-level Data. Data from two data loggers were used to quantify water-level fluctuations on both sides of the culvert, one placed in West Falmouth Harbor proper, about 50 ft north of the culvert (#668), the other placed in Little Neck Bay, about 25 ft south of the culvert (#501) (Figure 3.3). Data collected over a 47-day period and over a 5-day period during a Spring tide cycle show water-level fluctuations in West Falmouth Harbor and Little Neck Bay (Figure 3.4). The significance of the culvert restriction on Little Neck Bay can be discerned in these hydrographs, which superimposes the tidal fluctuations in West Falmouth Harbor (blue) at the downstream side of the embayment over the water-level fluctuations in Little Neck Bay (red).

Water levels fluctuate about 6.1 ft in West Falmouth harbor, ranging from elevation[2] +3.3 ft to -2.8 ft (Tables 3.3 and 3.4). In contrast, hydrologic fluctuations in Little Neck Bay, while driven by tides, are extremely muted, i.e., water levels only fluctuate about 0.8 ft in Little Neck Bay, at around elevation 0.8 to 1.6 ft (Table 3.3, Figure 3.4A) over a monthly tidal cycle.

[1] RTK= real-time-kinematic survey
[2] All elevations relative to NAVD88.

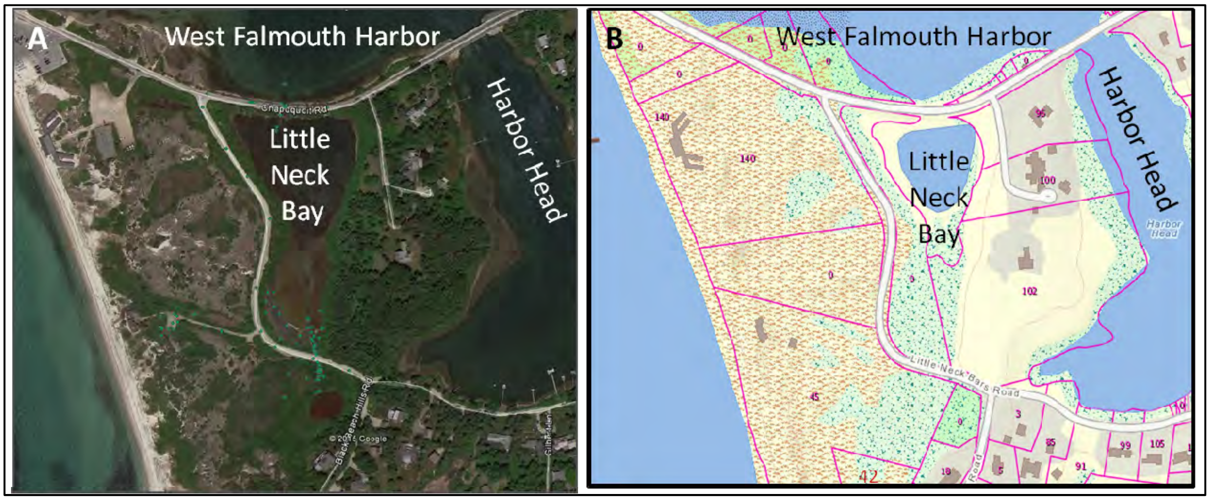

Figure 3.1. Location of Little Neck Bay relative to West Falmouth Harbor: (A) turquoise dots are locations of RTK points collected in and near Little Neck Bay, (B) parcel map (Mass GIS) of properties abutting Little Neck Bay.

Table 3.1. Characteristics and location information for the restrictive culvert under Chapaquoit Road, which connects Little Neck Bay to West Falmouth Harbor. RTK point numbers correspond to data points in a digital file accompanying the report.

Culvert Name (Location)	Northing[1]	Easting	Invert RTK point	Invert Elevation	Obvert RTK point	Obvert Elevation	Pipe diameter (ft)
Chapaquoit Rd (downstream: West Falmouth Harbor)	2679617.715	890048.113	102	-1.07	103	0.1305	1.0
Chapaquoit Rd (upstream: Little Neck Bay)	2679573.728	890043.828	107	0.51	108	1.6322	2.0

[1] All coordinates relative to NAVD88

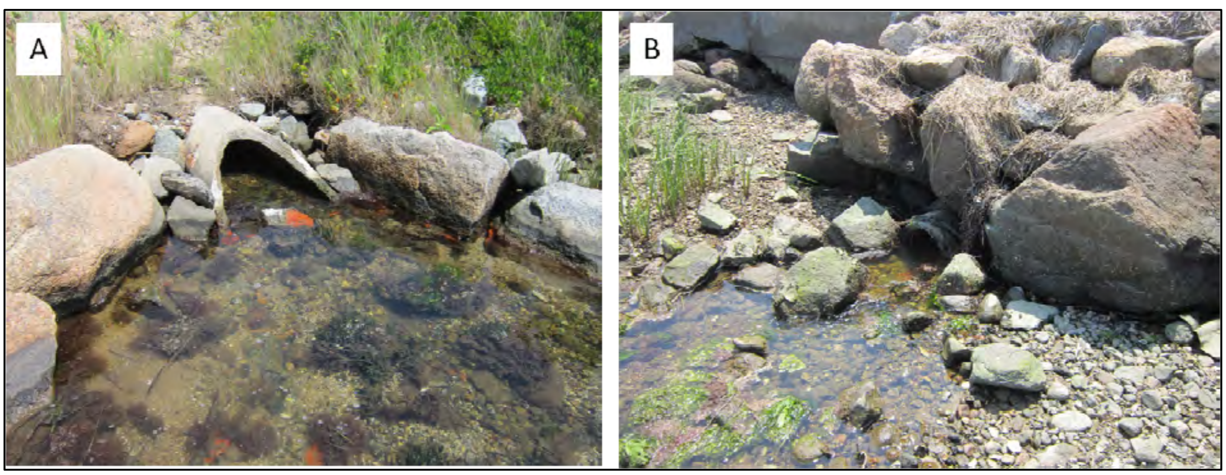

Figure 3.2. Culvert under Chapaquoit Road, connecting West Falmouth Harbor and Little Neck Bay: (A) culvert opening on the upstream, Little Neck Bay side , (B) culvert opening on the downstream, West Falmouth Harbor side. (Note: although the tide is lower than the culvert, some outflow from upstream is still occuring.)

Table 3.2. Summary elevations for natural features and infrastructure near Little Neck Bay, from RTK data. RTK point numbers correspond to data points in a digital file accompanying the report.

Cover type	Mean Elev.[1]	Min Elev.	Max Elev	Number of observations
Spartina alterniflora marsh (Little Neck Bay))	0.9971	0.6734	1.3026	11
Phragmites /marsh ecotone (Little Neck Bay)	1.7174	1.5869	1.8479	2
Shrub/marsh ecotone (Little Neck Bay)	1.0622	0.9509	1.1526	8
Sidewalk along Chapaquoit Road	6.2138	5.9239	6.4836	7
Little Neck Bars Road (unpaved)	4.3980	3.1173	6.6053	12
45 Little Neck Bars Road	2.8417	2.0671	3.6967	10
42 Black Beach Hills Road	4.1869	3.0147	4.8402	14

[1] All coordinates relative to NAVD88

Figure 3.3. Locations of data loggers at the Chapaquoit Road culvert downstream (#668) in West Falmouth Harbor and upstream (#501) in Little Neck Bay. The arrow points to the location of the culvert on the upstream (south side) of the restriction.

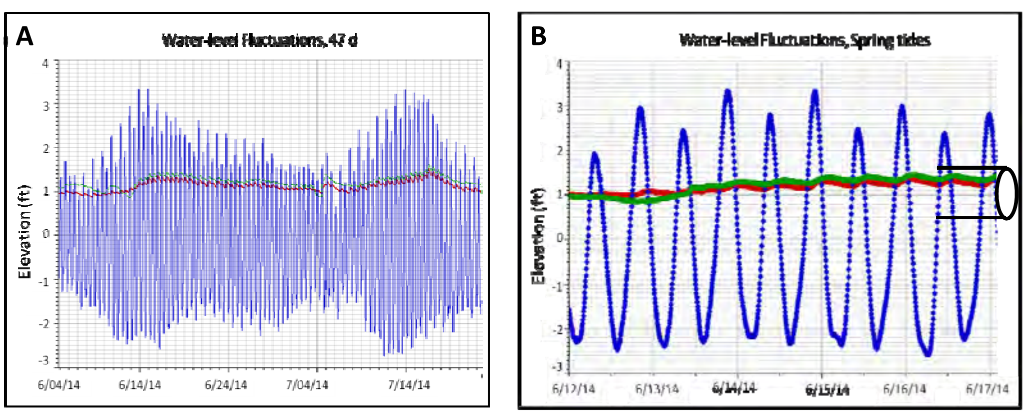

Figure 3.4. Water level fluctuations in West Falmouth Harbor (blue) and Little Neck Bay (red): (A) fluctuations over the 47-day period of record, (B) fluctuations over 5 days during Spring tides. Chapaquoit Road culvert position and size shown on right.

Table 3.3. Summary hydrologic statistics for West Falmouth Harbor and Little Neck Bay (upstream from the under the Chapaquoit Road culvert). Tidal statistics are not applicable for Little Neck Bay due to the severity of tidal dampening.

Summary statistics[1]	W. Falmouth Harbor	Little Neck Bay
MHHW: Mean Higher-High Water[2] (ft)	2.31	na
MHW: Mean High Water (ft)	2.05	na
MTL: Mean Tide Level (ft)	0.06	na
MLW: Mean Low Water (ft)	-1.94	na
MLLW: Mean Lower-Low Water (ft)	-2.04	na
Tidal Maximum (ft)	3.33	na
Tidal Minimum (ft)	-2.75	na
Mean Tide Range (ft)	3.99	na
Tide Range Ratio	na	
Tide Dampening	na	
Phase Delay (minutes)	na	

[1]Metrics were calculated based upon specific gravity of seawater
[2] All coordinates relative to NAVD88

Table 3.4. Variability of water-level level fluctuations for West Falmouth Harbor and Little Neck Bay (upstream from the culvert under Chapaquoit Road).

Location	Mean Water Level[1]	Max Water Level	Min Water Level	Range (ft)	1st Quartile Elev	3rd Quartile Elev	Quartile Range (ft)
West Falmouth Harbor	0.06	3.33	-2.75	6.08	n/a	n/a	n/a
Little Neck Bay	1.13	1.53	0.86	0.67	1.035	1.211	0.176

[1] All coordinates relative to NAVD88

These hydrographs show that the culvert under Chapaquoit Road not only mutes tidal exchange with Little Neck Bay, ranging only 0.6 ft (at about elevation +1.1 ft) during the period of record, but that it also maintains water height in Little Neck Bay at the upper 25% of the tidal curve (Figure 1.4: red line). Further, the main ditch was only about 0.65 ft deep in Little Neck Bay (mean thalweg elevation about +0.57 ft), meaning that there was only about 0.6 ft of water in the ditch, on average, with fluctuations only about 0.7 ft. The water table does seem to rise and fall slightly in response to daily tides and rises and falls somewhat in response to the lunar tidal cycle. Even so, freshwater input may contribute somewhat to water table fluctuations, particularly after storm events. However, the watershed of Little Neck Bay is quite small relative to the size of the embayment and so the overall contribution of freshwater input [(Precipitation + groundwater) – (ET)] is probably also quite small.

3.1.3 Vegetation. Vegetation was quantitatively sampled between 25 June and 3 July, 2014. Little Neck Bay shows a zonation of vegetation typical of coastal fringing wetlands. The inner, most saline zone supported salt-tolerant, salt marsh vegetation, usually *Spartina alterniflora* (saltmarsh cordgrass) and *S. patens* (salt hay). Landward of the salt marsh, a zone of *Phragmites australis* (common reed) sometimes occurs where nitrogen-laden groundwater is being discharged at the upper elevation edge of the marsh[3]. Alternatively, some portions of the salt marsh border is fringed by saline-tolerant and freshwater woody plants[4] (with little or no *Phragmites*) along undeveloped portions of the ecotone, where vegetation is undisturbed presumably where nitrogen input is less. Landward of the *Phragmites* zone, where present, there is usually a vegetated zone dominated by tall (2-3 m high) shrubs.

Little Neck Bay is about 6.2 acres (2.5 ha) in size, including wetlands and open water. The upper (southerly) end of the bay is extremely shallow, comprised mostly of salt marsh and mud flat (Figure 1.5). Tidal fluctuation in this embayment is extremely muted relative to the downstream side of the culvert in West Falmouth Harbor (tidal fluctuations are discussed in a later section).

A shallow (0.8 m deep), periodically-maintained mosquito ditch runs through the upper section of the Little Neck Bay. Spoil alongside this ditch support salt-tolerant shrubs, mostly *Baccahris halimifolia* (Groundsel) and *Iva frutescens* (marsh elder). This ditch is periodically maintained by the Cape Cod Mosquito Control District (Gabrielle Sakolsky, pers. comm.). Near the ditch, there are bleached snags (dead trees), suggesting that the upper end of the embayment must have at one time supported salt-intolerant trees. Saltwater intrusion during an extreme storm event probably killed the trees.

Eleven 1-m^2 plots were sampled in this embayment: four in the salt marsh flat, three in the *Phragmites*-dominated marsh fringing the upper marsh, and three plots in the tall shrub type at the wetland/upland ecotone landward of the *Phragmites* zone (Table 3.5). The salt marsh flat proper was dominated by *Spartina alterniflora* (short form) and *S. patens.* Detritus, dead plant material from the previous growing season, ranged from a trace amount to 85% of the plots. A band of *Phragmites,* generally ranging in width from 2-6 m, occurred at the landward edge of the salt marsh. This band was narrow to non-existent at the lower end of the marsh, but was 3-6 m wide at the upper end. In all, about 40% of the marsh had a band of *Phragmites* at its landward edge, primarily at the upper end of the embayment. *Phragmites* coverage ranged from 37-62% with 30-50 stems per m^2. Detritus in the 1-m^2 plots varied widely, covering from 2.5-85% of each plot.

Beyond the *Phragmites* zone (where it occurred), there was a wetland transition zone dominated by tall shrubs, inlcuding *Baccahris halimifolia, Myrica pensylvanica* (bayberry), and *Vaccinium corymbosum* (highbush blueberry). In some areas, particularly in the lower end of the embayment, the shrub zone bordered salt marsh without a intervening *Phragmites* zone. The shrub thicket had many vines weaving among them, including *Lonicera morrowii* (Morrow's honeysuckle, an invasive species), *Rhus radicans* (poison ivy), *Vitis aestivalis* (Summer grape), and *Parthenocissus quiquefolia* (Virginia creeper).

[3] *Phragmites* is a tall, clonal, invasive species that often grows in dense, monospecific stands and thrives where fresh water, dissturbance, and nutrient enrichment occur (Bertness et al. 2002, Silliman and Bertness 2004)
[4] *Clethra alnifolia, Vaccinium coymbosum, Rhododendron viscosum, Myrica pensylvanicum*

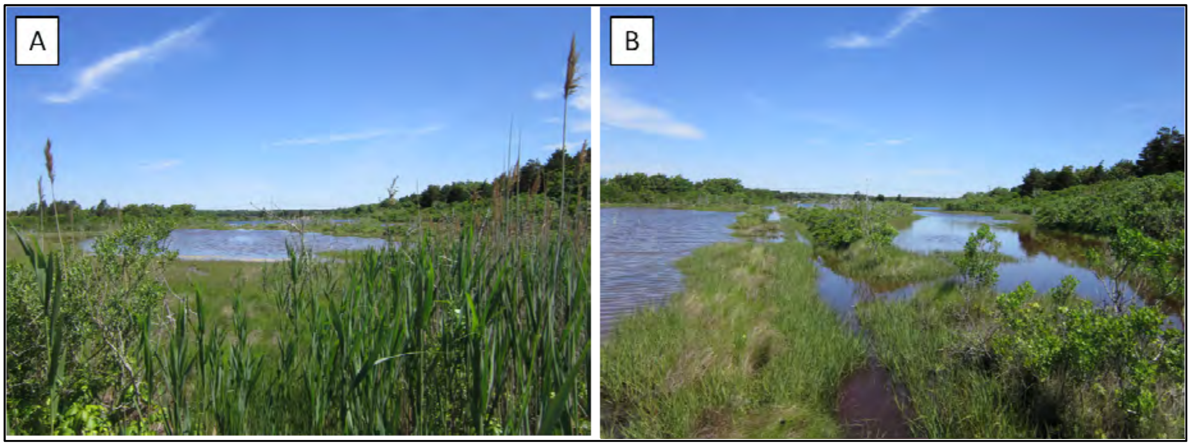

Figure 3.5. Views of Little Neck Bay: (A) looking north from Little Neck Bars Road with a Phragmites fringe in foreground, (B) mosquito ditch with a shrub line growing on a spoil berm on the right side of the ditch. Snags are seen in the distance, center of picture.

Table 3.5. Percent cover of vegetation in Little Neck Bay for three cover types in 11 x 1-m² plots.

	Salt Marsh					Phragmites			High Shrub		
Spartina alterniflora	37.5	50.0	62.5	15.0	-	-	-	-	-	-	-
Spartina patens	37.5	-	-	62.5	-	-	-	-	-	-	-
Gaylusacchia baccata	-	-	-	-	85.0	-	-	-	-	50.0	
Myrica pensylvanica	-	-	-	-	50.0	-	-	-	-	2.5	85.0
Phragmites australis	-	-	-	-	-	62.5	37.5	50.0	-	-	15.0
Baccharis halimifolia	2.5	-	-	-	-	15.0	2.5	37.5	85.0	15.0	2.5
Schoenoplectus pungens	-	-	-	-	-	15.0	37.5	-	-	-	-
Parthenocissus quinquefolia	-	-	-	-	-	-	-	37.5	15.0	-	2.5
Rhus radicans	-	-	-	-	-	-	-	15.0	37.5	15.0	-
Rosa palustris	-	-	-	-	-	-	-	15.0	-	-	-
Thelypteris palustris	-	-	-	-	-	-	-	15.0	-	-	-
Lonicera morrowii	-	-	-	-	-	-	-	-	37.5		-
Smilax herbacea	-	-	-	-	-	-	-	-	-		2.5
Sorbus americana	-	-	-	-	-	-	-	-	-	2.5	-
Vaccinium corymbosum	-	-	-	-	-	-	-	-	-	37.5	-
Vitus aestivalis	-	-	-	-	-	-	-	-	-	-	15.0
Unidentifiable mint	2.5	-	-	-	-	-	-	-	-	-	-
Detritus	15.0		37.5	15.0	-	2.5	37.5	85.0	-	-	-

3.1.5 Spatial distribution of marsh cover-types. Little Neck Bay supports seven distinctive marsh cover types: *Spartina alterniflora* and *S. patens* marshes, fringing *Phragmites* marsh, low shrub, high shrub, mud flat, and salt panne. The estimated spatial distribution among these types was manually drawn in the field on aerial photos and transferred digitally to maps (Figure 3.6). This spatial distribution of cover types on these maps provides a baseline to compare changes in cover types after culvert enlargements have been completed, bearing in mind that it might take several years for vegetation changes to fully take place after tidal exchange is improved.

Figure 3.6. Spatial distribution of marsh cover-types in Little Neck Bay. Abbreviations: P= Phragmites, Sa= Spartina alterniflora, Sp= Spartina patens, Hs= high shrub, Ls= low shrub, M= mud flat, Pa= salt panne.

3.1.6 Properties and Infrastructure. Eight properties abut the Little Neck Bay proposed project site, of which three are unimproved (Figure 3.1B). Lidar (Light Detection and Ranging) remote sensing data for the study area suggests that most infrastructure (houses, roads, utilities) on and near these properties are currently above the elevation of tides in West Falmouth Harbor (max= +3.3 ft) or protected by raised roadways. However, if full (unrestricted) tidal exchange were restored to Little Neck Bay, Spring tide heights in Little Neck Bay would increase by 1.5-2 ft, and drop by about 2 ft at low tides (if the upstream invert is lowered to the downstream invert elevation). Thus, unrestricted high tides would probably breach Little Neck Bars Road. A storm surge could even breach the road during lower lunar tides.

3.1.7 Hydraulic modeling results. Hydrologic modeling (Woods Hole Group, Appendix) showed that Chapaquoit Road will be overtopped by a FEMA 4-y storm event[5], at which time culvert size will be moot, since Little Neck Bar Road would be overtopped as well. Several culvert sizes (1-4 ft diameter) and culvert invert elevations (0.5 and -1.0 ft NAVD88) were modeled to compare normal tide and storm responses under the various storm scenarios relative to existing conditions and how such floods would

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[5] This refers to the FEMA storm surge return interval (44 CFR 59). A 4-y flood event means that there is a probability of a flood event occurring at a given height or higher once in four years or a 0.25 probability in any given year.

0.51 is correct

affect Little Neck Bars Road and the freshwater shrub bog on the south side of the road. The modeling found that small increases in the culvert diameter under Chapaquoit Road would result in large increases in tidal exchange and that dropping the culvert invert to 0.05 to -1.0 ft would also increase drainage. A 4-ft diameter culvert under Chapaquoit Road with -1.0 ft invert elevation (Table 3.6) would maximize tidal exchange (and hence, habitat), maximize safety, and minimize shoaling potential. While this configuration would not lead to an overtopping of Little Neck Bars Road during normal tides, it would allow the road to be overtopped during frequent, relatively weak storm events. This would require installing and managing a tide gate on the culvert and/or raising Little Neck Bars Road about 3 ft to equal that of the Chapaquoit Road elevation.

As an alternative to restoring a complete tidal prism, the best option would be to replace the 1.0-ft diameter culvert with a 1.25-ft diameter culvert and lowering the invert elevation from 0.5 ft to 0.0 ft NAVD88. This option would result in the overtopping of Little Neck Bars Road only during 4-y storm events, because Chapaquoit Road would also be overtopped then. This seemingly small change in culvert diameter would increase the intertidal area of Little Neck Bay by a factor of five and the tidal prism by a factor of eight. This is because the embayment is so shallow that a substantial proportion of the bay's depth is exposed with minor changes in tidal elevation. This option would also decrease the turnover period of the estuary from six days to less than one day. Another effect is that it would only take 1.5-3 days to return to equilibrium water levels following a 3-y storm event, versus 12 days under the current condition.

Table 3.6. Comparison of tide data between existing conditions and several larger replacement culverts for Little Neck Bay.

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

3.1.8 Conclusions. Little Neck Bay supports a moderate amount of the invasive species *Phragmites australis*, mostly near the upland/wetland ecotone, but less than most marshes degraded by reduced tidal flushing. It is anticipated that increased flooding in response to removing culvert restriction would likely increase nutrient exchange with the marsh and reduce the area of *Phragmites* coverage by allowing saline water to reach higher elevations.

There are no properties low enough to be flooded by a completed restoration of normal tidal exchange (and breach of Little Neck Bars Road) because any event greater than the 4-y storm event would breach Chapaquoit Road anyway and so culvert dimensions would be moot at that point. However, although culvert sizes ≥ 4 ft would provide maximize the ecological benefit, they would lead to frequent breaching of Little Neck Bars Road during relatively minor storm events unless storm effects were managed by a tide gate or the road were raised by 3 ft. Alternatively, increasing the culvert diameter of the culvert by only 0.25 ft, from 1.0 ft to 1.25, and lowering the invert elevation from 0.5 ft to 0.0 ft NAVD88 was predicted to provide the optimal improvement that it would not overtop Little Neck Bars Road at less than a 4-y event. Although this option would not lead to complete tidal restoration, it would increase the intertidal area of Little Neck Bay by a factor of five, increase the tidal prism by a factor of eight, decrease the residence time from six days to less than one 1 day, and allow a 3-y storm tide to drain in 1.5 days.

3.1.9 Summary. Little Neck Bars Road would likely be flooded by minor storm tides if unrestricted tidal exchange were completely restored to Little Neck Bay. However, if a new replacement culvert is somewhat restrictive (i.e., not allowing full tidal exchange), then breaching could be prevented except during events that would overtop Chapaquoit Road. Of equal concern is the fact that at the lower range of the tidal prism, drainage would not change much unless the upstream sill and the invert are also lowered. Results of a hydrologic modeling shows that increasing the culvert diameter of the culvert from 1.0 ft to 1.25 and lowering the invert elevation from 0.5 ft to 0.0 ft NAVD88 was the optimal culvert configuration for restoring partial ecological functioning in Little Neck Bay, without increasing susceptibility of Little Neck Bars Road to being overtopped during storm events.

3.2 Shrub Bog

3.2.1 Location. Shrub Bog is a sub-embayment of Little Neck Bay. It is located upstream (and south) of Little Neck Bars Road (Figure 3.7). Little Neck Bars Road is a 20-ft wide, dirt road that crosses the upper end of Little Neck Bay, separating Little Neck Bay from an embayment (Shrub Bog) to the south of the road. A culvert under this road, composed of a corregated pipe 0.5 ft in diameter and about 30 ft long, hydrologically connects Shrub Bog to Little Neck at the eastern end of the embayment (Table 3.7). Shallow ditches (0.7 to 1.3-ft deep) lead to both sides of this culvert, and although they are frequently maintained, they do not appear to transport much water to or from the culvert (Figure 3.8).

RTK data were collected for points along Little Neck Bars Road, on the bog surface, in cross-sections of ditches, and at the base of lowest-lying infrastructure on the five private properties abutting the bog, (Figure 3.8A). Elevations of important man-made and natural features are provided in Table 3.8. Raw RTK data, including local benchmarks, and the names and contact information for abutters is provided in the digital file accompanying this study.

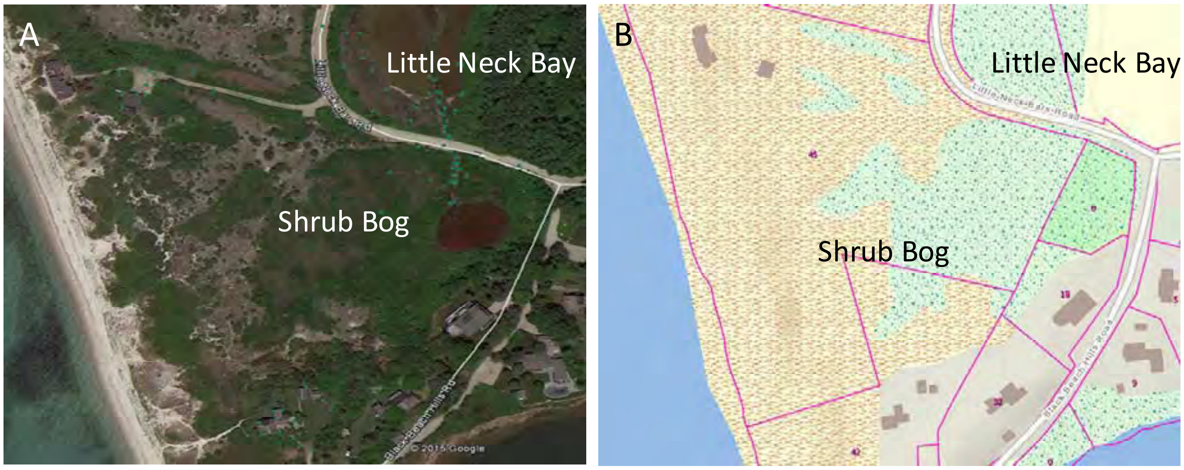

Figure 3.7. Location of Shrub Bog relative to Little Neck Bay: (A) turquoise dots are locations of RTK points collected in and near Shrub Bog, (B) parcel map (Mass GIS) of abutting properties.

Table 3.7. Characteristics and location information for the culvert under Little Neck Bars Road connecting Shrub Bog to Little Neck Bay. RTK point numbers correspond to data points in a digital file accompanying the report.

Culvert	Northing[1]	Easting	Invert RTK point	Invert Elevation	Obvert RTK point	Obvert Elevation	Diameter (ft)
Little Neck Bars Rd (downstream: Little Neck Bay)	2678717.67	890180.47	124	0.4818	125	1.2941	0.5
Little Neck Bars Rd (upstream: Shrub Bog)	2678678.91	890191.19	123	0.7175	123.5	1.2175	0.5

[1] All coordinates relative to NAVD88

Figure 3.8. Culvert under Little Neck Bars Road, connecting Shrub Bog to Little Neck Bay: (A) culvert opening on downstream, Little Neck Bay side, (B) culvert opening on upstream, Shrub Bog side.

Table 3.8. Summary elevations for natural features and infrastructure near Little Neck Bay, from RTK data. RTK point numbers correspond to data points in a digital file accompanying the report. Overt elevation (top of culvert) for 123.5 derived from field measurement was not surveyed. RTK= real-time-kinematic survey.

Cover type	Mean Elev.[1]	Min Elev.	Max Elev	Number of observations
Shrub wetland (Shrub Bog)	1.6976	1.4379	1.9268	4
Little Neck Bars Road (unpaved)	4.3980	3.1173	6.6053	12
45 Little Neck Bars Road	2.8417	2.0671	3.6967	10
42 Black Beach Hills Road	4.1869	3.0147	4.8402	14
[1] All coordinates relative to NAVD88				

3.2.2 Water-level Data. A pressure transducer data logger was installed on the upstream side the culvert, in Shrub Bog. The water level recorder located in Little Neck Bay was used as the downstream water level recorder. Thus, the downstream data logger was used for both embayments, i.e., as the upstream data logger for Little Neck Bay and the downstream data logger for the Shrub Bog. The logger in West Falmouth Harbor was used as the baseline for natural tidal prism.

Thus, data from three data loggers were used to quantify water-level fluctuations, the one in West Falmouth Harbor proper, about 50 ft north of the Little Neck Bay culvert (#668), one in Little Neck Bay, about 25 ft south of the culvert (#501), and one in a mosquito ditch in the Shrub Bog (#500) (Figure 3.9). An atmospheric logger was also placed near the water-level logger in Shrub Bog.

Data collected over a 47-day period and over a 5-day period during a Spring tide cycle show water-level fluctuations in these locations (Figure 3.10). The hydrograph superimposes tidal fluctuations in West Falmouth Harbor (blue) over the water-level fluctuations in Little Neck Bay (red) and Shrub Bog (green). Water levels fluctuate about 6.1 ft in West Falmouth Harbor, ranging from elevation[6] +3.3 ft to -2.8 ft (Table 3.9). In contrast, hydrologic fluctuations in Shrub Bog, are extremely muted, i.e., water levels only fluctuate about 0.8 ft, at around elevation 0.8 to 1.6 ft, only slightly higher than in Little Neck Bay.

The impact of the Chapaquoit Road culvert restriction is the same for Shrub Bog as it is for Little Neck Bay, as evidenced by the similar hydrographs for both embayments. Thus, the small culvert draining Shrub Bog (under Little Neck Bars Road) is not the main impediment to tidal exchange. The primary tidal restriction is downstream, at the culvert under Chapaquoit Road. This means that a restoration of tidal exchange to Shrub Bog is dependent on restoration of tidal flow to Little Neck Bay.

[6] All elevations relative to NAVD88.

Figure 3.9. Location of the data logger in Shrub Bog (#500), upstream of the culvert to connecting shrub Bog to Little Neck Bay. The arrow points to the location of the culvert on the upstream (south side) of the restriction.

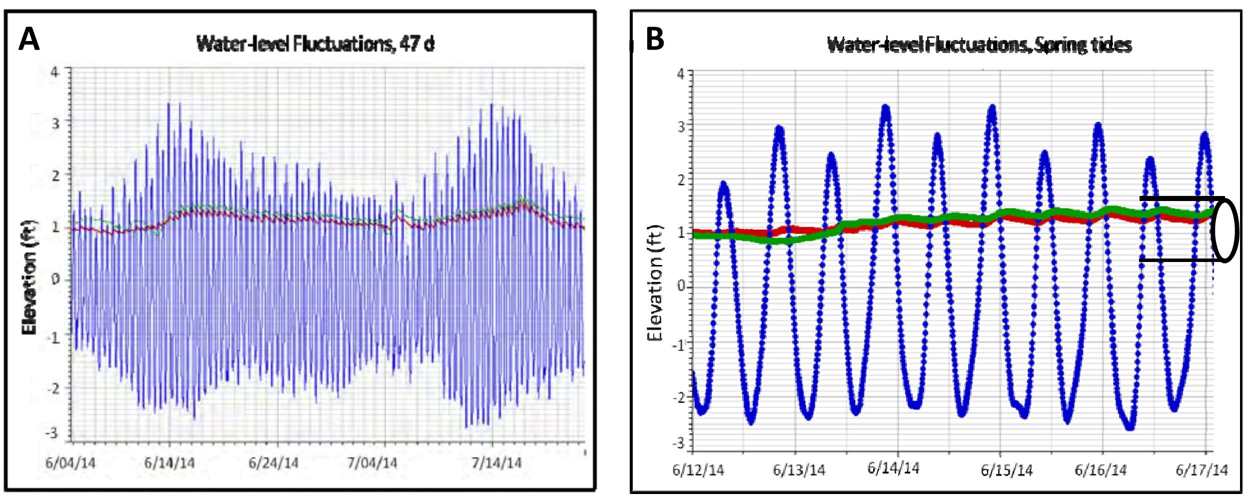

Figure 3.10. Water level fluctuations in West Falmouth Harbor (blue), Little Neck Bay (red), and Shrub Bog (green): (A) fluctuations over the 47-day period of record, (B) fluctuations over 5 days during Spring tides. Chapaquoit Road culvert position and size shown on right.

Table 3.9. Variability of water-level level fluctuations (elevations) for West Falmouth Harbor, Little Neck Bay, and Shrub Bog.

Location	Mean Water Level[1]	Max Water Level	Min Water Level	Range (ft)	1st Quartile Elev	3rd Quartile Elev	Quartile Range (ft)
West Falmouth Harbor	0.06	3.33	-2.75	6.08	n/a	n/a	n/a
Little Neck Bay	1.13	1.53	0.86	0.67	1.035	1.211	0.176
Shrub Bog	1.22	1.63	0.85	0.78	1.140	1.315	0.175

[1] All coordinates relative to NAVD88

A frequently-maintained mosquito ditch runs from the culvert to a small pond (~ 800 m^2 in size) and to the middle of the bog. The ditch was probably primarily dug to drain the pond, but due to its depth and the elevation of the culvert invert, it has probably only been successful on somewhat lowering the surface elevation of the pond. An RTK survey was used to determine cross-section morphology of the ditch in the Shrub Bog, by measuring from top-of-bank to thalweg (deepest point) to top-of-bank on the opposite side. The top of bank was about at +1.8 ft and the bottom was about +0.5 ft (mean elevations), meaning that the thalweg was about 1.3 ft deep, on average. Since the mean water table in Shrub Bog was +1.2 ft over the period of record, the water table was about 0.6 ft below the surface of the bog. This means there was usually about 0.7 ft of water in the ditch, on average, throughout the study period. Fluctuation was only about 0.8 ft, so the water levels never overtopped the ditch bank.

As was the case for Little Neck Bay, the water table does seem to rise and fall slightly in response to daily tides and rises and falls somewhat in response to the lunar tidal cycle. As with Little Neck Bay, freshwater input may contribute somewhat to water table fluctuations in Shrub Bog, particularly after storm events. However, the watershed of Shrub Bog, although slightly larger than Little Neck Bay, is still quite small relative to the size of the embayment. Thus, the overall contribution of freshwater input [(Precipitation + groundwater) – (ET)] is probably quite small relative to tidal fluctuations.

3.2.3 Condition of Vegetation. The Shrub Bog is a geomorphic extension of Little Neck Bay that has been physically and hydrologically separated by Little Neck Bars Road. Although a small culvert hydrologically connects the two embayments, flow between them is minimal. This has led to conversion of the southern side of the road to a plant community dominated by shrubs over most of its area. This is in contrast to the northern side of the road (Little Neck Bay), which is dominated by salt marsh in its center and shrubs only on its margins, at the wetland/upland ecotone.

A fringe of *Phragmites* occurs along the eastern and southern ends of a small pond in the bog and at the southeastern end of the bog, but most of the bog is covered by a rich community of low (< 1-m tall) and high (> 1-m tall) shrubs interspersed with salt-intolerant herbaceous plants (Figure 3.11). Nine species of shrubs were encountered in eight 1 m^2 plots, but many more species were observed (Table 3.10). Five of the nine species were ericads (heaths), one of which was *Vaccinium macrocarpon* (cranberry). Among the many ericads, there are patches of sundews, especially *Drosera intermedia* (spatulate-leaved sundew) and *D. filiformis* (thread-leaved sundew). Since the bog is very rich in species, both woody and herbaceous, it would be worthy of a more detailed species inventory if it were decided to restore tidal incursions there. (The bog's composition does not fit any of the descriptions of natural communities recognized by the Massachusetts Natural Heritage Program.) It would also be worthwhile discussing the mangers of the Salt Pond Bird Sanctuary, which owns 0 Black Beach Hills Road, regarding any possible plans.

Figure 3.11. View of Shrub Bog vegetation, looking northwest.

Table 3.10. Percent cover of vegetation in the Shrub Bog for three cover types in 8 x 1 m² plots. T= trace (< 1%).

Species	**Low Shrub**					**High Shrub**		
Gaylusacchia baccata	62.5	37.5	-	-	-	-	-	-
Sorbus americana	32.5	37.5	50.0	62.5	37.5	-	85.0	37.0
Kalmia angustifolia	15.0	-	2.5	2.5	15.0	-	15.0	-
Myrica pensylvanica	-	-	2.5	15.0	15.0	2.5	15.0	50.0
Vaccinium macrocarpon	-	2.5	50.0	37.5	85.0	-	-	-
Rubus hispidus	-	-	50.0	15.0	-	-	-	-
Andropogon glomeratus	-	2.5	37.5	62.5	2.5	-	-	-
Lyonia ligustrina	-	-	37.5	-	-	85.0	15.0	15.0
Rhus copallinum	-	-	15.0	-	-	2.5	-	-
Rhus radicans	-	-	2.5	15.0	-	-	2.5	-
Thelypteris palustris	-	-	-	2.5	-	-	-	2.5
Rhododendron viscosum	2.5	T	-	-	-	15.0	-	-
Viburnum dentatum	-	-	-	-	-	2.5	-	2.5
Parthenocissus quinquefolia	-	-	-	-	-	2.5	2.5	-
Aster sp.	-	-	-	-	-	-	-	2.5
Ilex opaca	-	T	-	-	-	-	-	-
Euthamia caroliniana	-	T	-	-	-	-	-	T
Unidentifiable dicot	-	-	-	-	T	2.5	2.5	15.0

3.2.4 Spatial distribution of marsh cover-types. Shrub Bog supports three distinctive cover types: *Phragmites* fringing marsh, low shrub, and high shrub. The estimated spatial distribution among these types was manually drawn in the field on aerial photos and transferred digitally to maps (Figure 3.12). This spatial distribution of cover types on these maps provides a baseline to compare changes in cover types after culvert enlargements have been completed, bearing in mind that it might take several years for vegetation changes to fully take place after tidal exchange is improved.

Figure 3.12. Spatial distribution of marsh cover-types in Shrub Bog. Abbreviations: P= Phragmites, Hs= high shrub, Ls= low shrub.

3.2.5 Properties and Infrastructure. Five properties are near the shrub bog, of which one is unimproved. Lidar remote sensing data for the study area suggests that most infrastructure (houses, roads, utilities) on and near these properties are currently above the elevation of tides in West Falmouth Harbor (max= +3.3 ft) or protected by raised roadways. Even if full (unrestricted) tidal exchange were restored to Little Neck Bay and thence, Shrub Bog, the properties would not be in danger of flooding except during 4-y or less frequent events. Such events would also overtop Chapaquoit Road and so it would be immaterial to the extent to which tidal flow is restored. However, Little Neck Bars Road would be flooded relatively frequently if the full tidal prism were restored, which would prevent travel to and from homes accessed by the road.

3.2.6 Conclusion. The culvert separating West Falmouth Harbor from Little Neck Bay is the main impediment dampening the tidal prism in both Little Neck Bay and Shrub Bog, i.e., the tidal prism can not be restored to Shrub Bog without also restoring it Little Neck Bay. Currently, the culvert under Little Neck Bars Road prevents salt water in Little Neck Bay from infiltrating the Shrub Bog, evidenced by the fact that plant communities in Shrub Bog are comprised of freshwater species. Water-level fluctuations occur 0.2 to 1 ft below the surface of the bog and mimic those in Little Neck Bay. However, the fluctuations occur slightly higher in elevation (mean 0.1 ft higher), perhaps because there is a freshwater lens overlying saltier water below.

The Shrub Bog supports a high number of freshwater species and deserves special attention because tidal flooding would drastically change the composition of the marsh, switching it from a relatively speciose freshwater shrub wetland to a salt or brackish marsh. Because of this, it is not recommended that tidal flow be restored to the bog. However, due to its low-lying position, a storm greater than a 3-y event, which would overtop Little Neck Bars Road, would also flood the shrub bog with saline water, and kill the freshwater species in it. With a rising sea level, such an event will become more likely over time. In any case, if the Little Neck Bars Road culvert were replaced, it might be advisable to provide a flap gate on the culvert so that water can drain from the bog and inhibit saline water from flooding it.

3.2.7 Summary. The culvert separating West Falmouth Harbor from Little Neck Bay restricts almost all fluctuations in Little Neck Bay and Shrub Bog. The culvert separating Shrub Bog from Little Neck Bay further restricts salt water intrusion into the bog, though it does nothing to dampen the already diminished tidal fluctuations. In any case, restoration of tides in Shrub Bog is not advisable and so tides should be prevented from entering the bog, when possible, while freshwater should be allowed to exit freely. Hence, a flap gate or similar structure will need to be considered for the culvert under Little Neck Bars Road if tidal flow is partially restored to Little Neck Bay.

3.3 Oyster Pond

3.3.1 Location. Oyster Pond is a subembayment of Harbor Head, which is in turn an extension of West Falmouth Harbor (Figure 3.13). Oyster Pond is separated from Harbor Head by a culvert under the Shining Sea Bike path, a paved, former railroad right-of-way The corregated culvert under the bike trail is 3.8 ft in diameter and is fairly new (Table 3.11, Figure 3.14). The outlet of the culvert and Harbor Head are connected by a 270-ft-long tidal creek, which is only 23 ft in width at the downstream end, at the location of an abandoned dike (Figure 3.15A). There is an 1.7-ft elevation gain along this channel to the culvet invert, then another 1.1-ft rise to a shoal on the upstream side of the culvert before reaching Oyster Pond proper (Figure 3.15B).

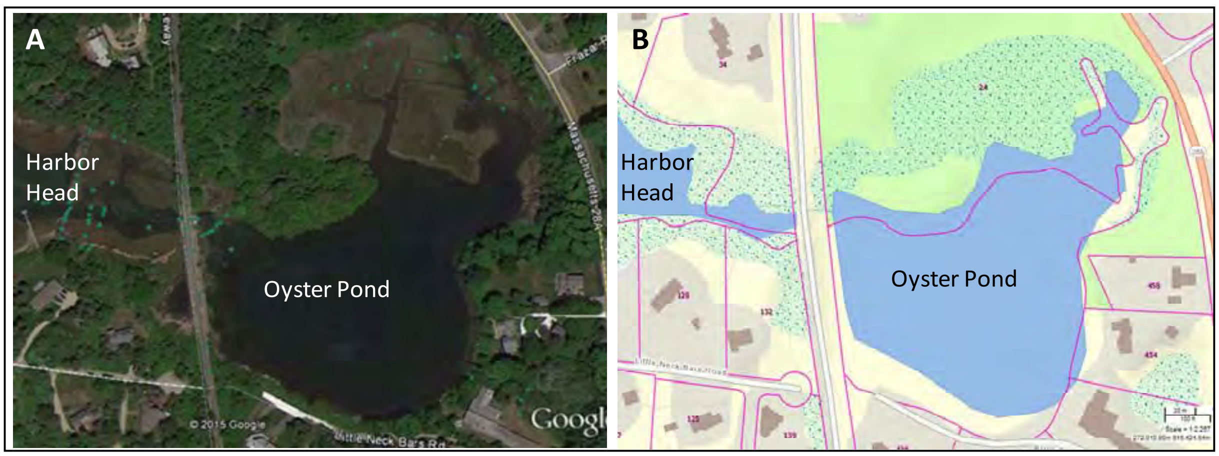

Figure 3.13. Location of Oyster Pond relative to Harbor Head: (A) turquoise dots are locations of RTK points collected in and near Oyster pond, (B) parcel map (Mass GIS) of abutting properties. A tidal creek connects Oyster Pond with Harbor Head.

Table 3.11. Characteristics and location information for the culvert under the Shining Sea Bike Trail, connecting Oyster Pond with Harbor Head. RTK point numbers correspond to data points in a digital file accompanying the report.

Culvert	Northing[1]	Easting	Invert RTK point	Invert Elevation	Obvert RTK point	Obvert Elevation	Diameter (ft)	Condition	Length (ft)
Shining Sea Bike path (downstream: tidal creek)	2678827.01	891700.23	58	-1.7818	8	1.7533	3.8	Good	40
Shining Sea Bike path (upstream: Oyster Pond)	2678826.77	891740.74	7	-1.7110	59	1.7269	3.8	Good	

[1] All coordinates relative to NAVD88

Figure 3.14. Views of culvert under Shining Sea Bike Path, connecting Harbor Head and Oyster Pond: (A) culvert opening on downstream, Harbor Head side, (B) culvert opening on upstream, Oyster Pond side.

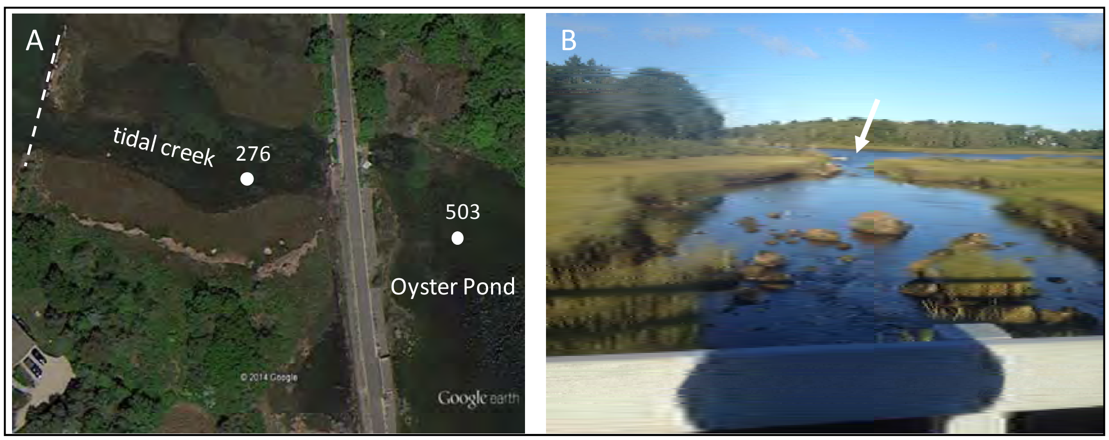

Figure 3.15. Views of tidal creek downstream of Oyster Pond: (A) path of former dike (white dashed line), (B) location of this creek looking east (downstream) from the bike trail. Arrow points to the constriction (narrowest portion) of the creek, at an abandoned dike.

RTK data were collected for points along the bike path, on the marsh surface on the tidal creek and Oyster Pond, in cross-sections of the shoal and three cross-sections of the tidal creek, along the abandoned dike, at the edge of the yard at the lowest-lying property (Figure 3.15A). Elevations of important man-made and natural features are provided in Table 3.12. Raw RTK data, including local benchmarks, and the names and contact information for abutters is provided in the digital file accompanying this study.

Table 3.12. Summary elevations for natural features and infrastructure in the vicinity of Oyster Pond, from RTK data. RTK point numbers correspond to data points in a digital file accompanying the report.

Cover type	Mean Elev.[1]	Min Elev.	Max Elev	Number of observations
Spartina alterniflora marsh (Oyster Pond)	1.320	0.975	1.673	5
Spartina patens marsh (Oyster Pond)	1.268	1.202	1.326	4
Phragmites /marsh ecotone (Oyster Pond)	1.354	0.844	1.666	5
Shrub/marsh ecotone (tidal Creek, Oyster	2.147	1.828	2.567	4
Spartina alterniflora marsh (tidal creek)	1.328	1.673	0.975	4
Tidal creek bottom	(2.3302)	na	na	1
Oyter pond shoal bottom	(0.6815)	na	na	1
Bike path (Oyster Pond)	6.967	6.209	8.544	6

[1] All coordinates relative to NAVD88

3.3.2 Water-level Data. A pressure transducer data logger was installed about 100 ft from the upstream side the culvert (#503), in Oyster Pond, and another (#276) about 75 ft downstream in the tidal creek (Figure 3.15A). Data collected over a 47-day period provide water-level fluctuations in West Falmouth Harbor, Oyster Pond, and the tidal creek (Figure 3.16). Summary statistics show the differences in tidal fluctuations among the three locations (Table 3.13). Comparisons among them show that the tide is restricted in the tidal creek relative to West Falmouth Harbor and even more restricted in Oyster Pond. This suggest that both the tidal creek and the culvert restrict tidal flow, although the culvert restriction might back up water in the creek and thus be partly responsible for the differences. There are appears to be a shoal in the creek just downstream from the culvert that may also restrict flow.

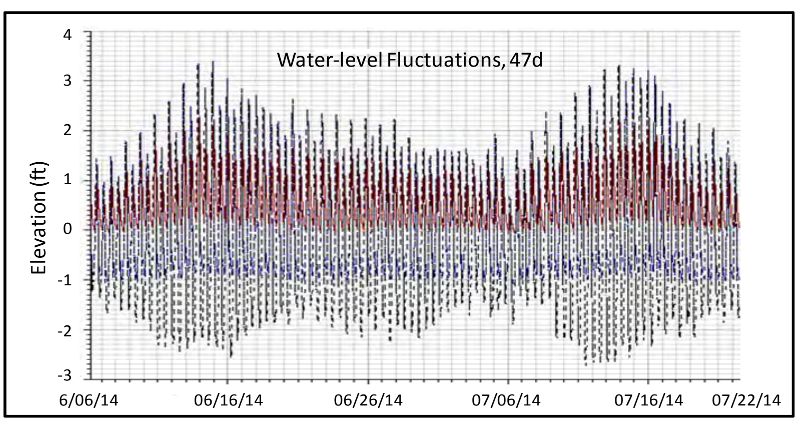

Figure 3.16. Water-level fluctuations located downstream of the culvert over a 47-day period in West Falmouth Harbor (black), Oyster Pond (red), and the tidal creek (blue).

Table 3.13 Summary tidal statistics for Oyster Pond and the down stream tidal creek relative to West Falmouth Harbor.

Metric	W. Falmouth Harbor (WFH)	Tidal Creek (downstream)	Oyster Pond (upstream)	Tidal Creek minus Oyster Pond	WFH minus Tidal Creek	WFH minus Oyster Pond
MHHW: Mean Higher-High Water[2] (ft)	2.31	2.35	1.60	0.75	(0.04)	0.71
MHW: Mean High Water (ft)	2.05	2.09	1.42	0.67	(0.03)	0.64
MTL: Mean Tide Level (ft)	0.06	0.57	0.74	(0.17)	(0.52)	(0.68)
MLW: Mean Low Water (ft)	(1.94)	(0.94)	0.06	(1.00)	(1.00)	(2.00)
MLLW: Mean Lower-Low Water (ft)	(2.04)	(0.98)	0.04	(1.01)	(1.07)	(2.08)
Tidal Maximum (ft)	3.33	3.39	2.27	1.12	(0.07)	1.06
Tidal Minimum (ft)	(2.75)	(1.10)	(0.07)	(1.04)	(1.64)	(2.68)
Mean Tide Range (ft)	3.99	3.03	1.36	1.67	0.97	2.63
Tide Range Ratio		45%				
Tide Dampening		1.27				
Phase Delay (minutes)		84 minutes				

[1]Tidal Metrics were calculated based upon specific gravity of saltwater
[2] All elevations relative to NAVD88

A clearer picture is seen when examining the fluctuations over a shorter time frame (Figure 3.17). Tidal waters flood through the culvert under the bike trail when the water level of Oyster Pond is at about elevation +0.2 ft. The culvert restriction reduces the rate of flooding of Oyster Pond, and hence dampens the height of flooding by about 1 ft relative to the tidal creek just downstream from the culvert, as depicted in Figure 3.17A. In fact, the rate of both flood and ebb for Oyster Pond (red line) are slower than the tide in the downstream tidal creek and in West Falmouth Harbor. There is also a lag during flood in that tides continue to flood Oyster Pond even as the tide begins to ebb in the tidal creek downstream from the culvert.

During ebb tides, when the elevation of water in the creek drops to the elevation of water in Oyster Pond (top arrow in Figure 3.17B), Oyster Pond begins to ebb as well. The rate of ebb in the pond is reduced relative to that of the creek due to the restrictive effects of the culvert. At about +0.7 ft, the rate of ebb slows further (top of box, Figure 3.17B), likely in response to bottom friction exerted by the shoal (elevation -0.7 ft), which is located about 43 ft upstream from the culvert (Figure 3.18). The rate of ebb is reduced further as the depth of water above the shoal become shallower. Without the shoal, but with the current culvert, water elevation in Oyster Pond could drop to about elevation -0.4 ft before the return of flood (lower arrow, Figure 3.17B). Thus, as a result of the shoal, about 0.6 ft is cut from the potential lower tidal prism of Oyster Pond, based on the slope of the dotted line. When the next flood tide of the creek reaches the water elevation of Oyster Pond 5-6 hours later, water again begins to flood into Oyster Pond, thus completing the cycle.

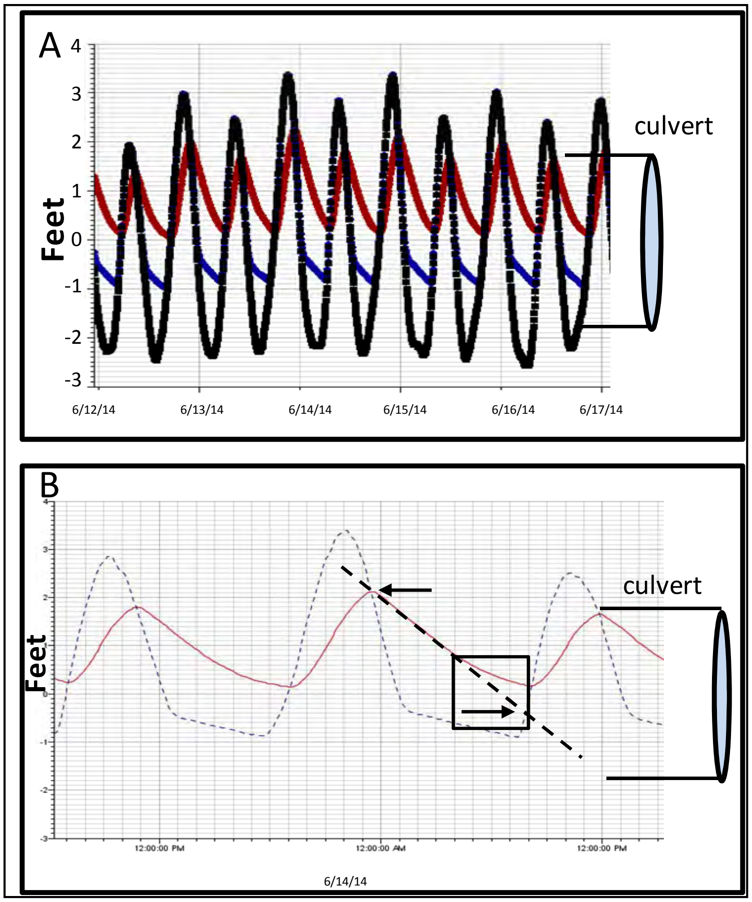

Figure 3.17. Water-level fluctuations for West Falmouth Harbor (black), Oyster Pond (red), and the tidal creek (blue), over (A) a 5-day period (during spring tides) and (B) over 24 hours. Dotted line shows slope of ebb flow rate

Interestingly, the ebb of the tidal creek also slows as the water in it becomes shallower. However, in contrast the change in rate upstream due to the shoal, the rate change is abrupt, is much more pronounced, and the rate does not decline with decreasing depth. The abrupt slowdown occurs when water level in the tidal creek reaches about -0.3 to -0.5 ft elevation[7] and continues at this rate for 6 hours until the flooding tide reverses flow. This reduction in the rate of ebb may be due entirely to bottom friction (there are many rocks and boulders in the creek), but it is also possible that it is accentuated by a hydraulic restriction of the creek.

To quantify the morphology of the tidal creek, three cross-sections (X-S) were measured across the creek: one downstream at a natural constriction before the creek empties into Harbor Head, one about 50 ft upstream, and another about 80 ft upstream (Figure 3.19). Results show that the creek bottom elevation rises from about 0.5 ft in elevation over this 80-ft distance, and another 0.3 ft to the culvert invert. However, the creek gets deeper at the midstream reach (pools).

[7] Interestingly, the depth at which slowdown occurs varies and the timing does not coincide with shoaling upstream; in fact, slowing of ebb in the creek occurs when the rate of ebb in Oyster Pond is at about its maximum.

Figure 3.18. View of a shoal constituting a 1.1-ft elevation rise on the upstream side of the Oyster pond culvert. Oyster pond proper is in the foreground.

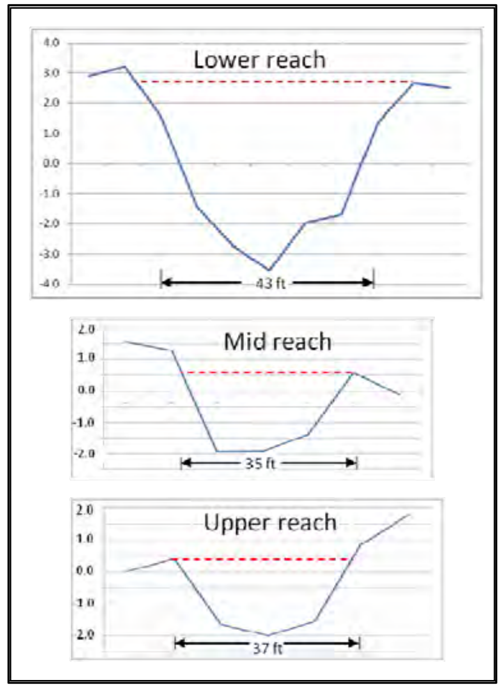

Figure 3.19. Cross-sections of the tidal creek emptying Oyster Pond, with channel widths indicated, are drawn to scale. Water-level logger was placed above the upper reach. Note elevation rise of thalweg from lower to upper part of the reach. Lower reach at the location of a former dike.

3.3.3 Vegetation. Some fringing salt marsh occurs along the western edge of Oyster Pond, at the base of the Shining Sea bike trail, but most occurs at the upper, northeast end of the pond. The marsh consists of about 8,300 m^2 (0.83 ha), mostly dominated by *S. alterniflora* and *S. patens* (Table 3.14). A fringing *Phragmites* zone, about 15 wide, occurs along the western and northern edges of the marsh. A narrow shrub zone occurs along the northwestern edge of the marsh and a narrow tongue extends into the southeastern end. Many small to large, unvegetated salt pannes are also scattered throughout the marsh, ranging from only a few m^2 to > 300 m^2 in size.

Interestingly, marsh areas near creeks and historic mosquito ditches are breaking up. That is, chunks are sloughing into the creek and the edges are riddled with hollow areas interspersed with unstable hummocks. The color of the marsh grass within these slough zones are a dark bluish-green, in contrast to the more emerald-green color of the intact marsh areas (Figure 3.20). Because grasses with high nitrogen content also tend to be bluer in color (Schertz 1929), this suggests that that the sloughing and marsh color could be indicators of nitrogen loading (eutrophication). In fact, the shoreline in front of 454 W. Falmouth Highway has a prolific growth of filamentous algae growing along the shoreline, an indicator of nitrogen-rich groundwater input.

Figure 3.20. Salt marsh on Oyster Pond, showing break-up of marsh into hummocks. Note the turquoise color of marsh grass where marsh is breaking up.

Table 3.14 Percent cover of vegetation in Oyster Pond for three cover types in 16 x 1 m² plots.

Species	**Salt Marsh**												**Phragmites**		**High Shrub**	
Spartina alterniflora	85.0	85.0	50.0	62.0	100.0	32.5	-	85.0	15.0	15.0	-	37.5	-	-	-	-
Spartina patens	-	15.0	-	-	-	15.0	37.5	-	85.0		50.0	50.0	-	-	-	-
Distichlis spicata	-	-	-	-	-	-	-	-	-	62.0	-	-	-	-	-	-
Schoenoplectus pungens	-	-	-	-	-	-	-			15.0	-	-	-	-	-	-
Mikania scandens	-	-	-	-	-	-	2.5	-	-	-	-	-	-	-	-	-
Phragmites australis	-	-	-	-	-	-	-	-	-	-	-	-	85.0	62.5		-
Vaccinium corymbosum	-	-	-	-	-	-	-	-	-	-	-	-	-	37.5	50.0	-
Vitus aestivalis	-	-	-	-	-	-	-	-	-	-	-	-	-	37.5	-	-
Clethra alnifolium	-	-	-	-	-	-	-	-	-	-	-	-	-	-	50.0	-
Myrica pensylvanica	-	-	-	-	-	-	-	-	-	-	-	-	-	-	15.0	15.0
Osmunda cinnamonea	-	-	-	-	-	-	-	-	-	-	-	-	-	-	15.0	-
Rhododendron viscosum	-	-	-	-	-	-	-	-	-	-	-	-	-	-	15.0	-
Rhus radicans	-	-	-	-	-	-	-	-	-	-	-	-	-	-	15.0	37.5
Rosa multiflora	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	50.0
Typha sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	15.0
Carex pensylvanicum	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2.5	-
Detritus	15.0	50.0	37.5	15.0	-	62.5	85.0	15.0	50.0	15.0	62.5	15.0	-	-	-	-
T= trace (<1%)																

Although salt marshes can assimilate excess nitrogen in tissues and it can be converted via various microbial pathways in marsh sediments (Burgin and Hamilton 2007), large inputs of nitrogen have been shown to cause marshes to allocate more biomass to leaves and less to roots, eventually leading to the physical deterioration (instability) of the marsh surface (Deegan et al. 2012).

Another potential cause of marsh instability is prolonged soil saturation of marsh sediments in response to the damming stress caused by the culvert restriction. Thus, two stresses, prolonged soil saturation and eutrophication, could both be responsible for the marsh's physical deterioration. Enhancing tidal exchange by enlarging the culvert would both reduce the period of marsh soil saturation and enhance the flushing rate of excess nitrogen from the system.

3.3.4 Spatial distribution of marsh cover-types. The study embayments support seven distinctive marsh cover types: *Spartina alterniflora* and *S. patens* marshes, *Phragmites* marsh, and salt panne. The estimated spatial distribution among these types was manually drawn in the field on aerial photos and transferred digitally to maps (Figure 3.21). This spatial distribution of cover types on these maps provides a baseline to compare changes in cover types after culvert enlargements have been completed, bearing in mind that it might take several years for vegetation changes to fully take place after tidal exchange is improved.

Figure 3.21. Spatial distribution of marsh cover-types in Oyster Pond. Abbreviations: P= Phragmites, Sa= Spartina alterniflora, Sp= Spartina patens, Pa= salt panne.

3.3.5 Hydraulic modeling results. Replacement of the 3.8-ft diameter culvert under the Shining Sea Bike path was modeled by determining the effects shoals have on tidal exchange and examining incrementally larger box culverts. The models indicated that upstream shoal and constriction of the tidal creek downstream are primarily responsible for restricting flow, but that the culvert size also is responsible for some of the attenuation. The upstream shoal is particularly restrictive because it prevents Oyster Pond from draining completely. If shoal is removed, a 4 X 4-ft box culvert was predicted to be the optimal size for maximizing tidal exchange. However, just lowering the shoal improves tidal characteristics even more than the replacing the culvert (Table 3.15) and increases flow velocities enough to probably prevent reshoaling. However, the larger culvert would be safer than the present one, since flow velocities will almost doubled if the shoal were removed. Thus, maximum tidal exchange can be achieved by both enlarging the culvert to 4 X 4 ft and removing the shoals. This will increase the tidal range by 2 ft, reduce residence time by from 3 days to 1 day, and reduce the time it takes for the water levels to return to equilibrium (normal conditions) following a 3-yr storm event.

Table 3.15. Tidal data comparison of existing and various alternatives at Oyster Pond.

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

3.3.6 Conclusion. Six properties abut Oyster Pond (Figure 3.24). The lowest-lying property is the yard at 438 West Falmouth Highway, which is at +5-7 ft elevation. Lidar remote sensing data for the study area (Figure 3.10) shows that infrastructure (houses, roads, utilities) on and near Oyster Pond are far above the elevation of storm tides (maximum West Falmouth Harbor= +3.3 ft), even after culvert replacement.

The culvert under the Shining Sea bike trail moderately restricts tidal flow to Oyster Pond. Lowering the upstream shoal to the invert elevation will result in a 1.6-ft increase in tidal range, halve the residence time, and result in 85% higher flow velocities. By both removing the shoals and replacing the culvert with a 4 by 4-ft box culvert, the optimal size, would increase the mean tidal range by an additional 0.54 ft, and although mean flood velocity would only increase by 0.4 ft/s, the flow would be through a 41% larger opening.

3.3.7 Summary. The vegetation of the marshes on Oyster Pond show signs of eutrophication (nutrient enrichment) and prolonged flooding and so would likely respond positively to increased tidal exchange. That said, removing the restrictive shoals, especially the one on the upstream side that prevents complete drainage of the pond, would improve tidal exchange tremendously. A slight additional improvement in residence time and mean tidal range could be gained by also replacing the present culvert with a 4 X 4-ft box culvert. In both cases, increased flow velocities would likely prevent the shoals from reforming.

There are no properties that would be at risk by restoring tidal flow to Oyster Pond, so none of the proposed improvements to tidal exchange would detrimentally affect property.

4. SUMMARY

Tidal fluctuations in Shrub Bog is dependent on tidal hydrodynamics of Little Neck Bay. Because Shrub Bog is a speciose freshwater ecosystem, it would be reasonable to continue to restrict tidal flow to it and, if tidal exchange to Little Neck Bay is restored, install a flap gate to prevent saline water from entering it. However, since both Chapaquoit Road and Little Neck Bars Road (which is lower) will both be inundated during a 4-y storm event, Shrub Bog is bound to receive saline water in the near future. When this happens, much of the freshwater vegetation will be negatively impacted.

Little Neck Bay is a severely-restricted embayment. However, restoring complete tidal exchange to it would cause Little Neck Bars Road to be overtopped during minor storms. The only way to avoid frequent overtopping would be to raise the elevation of the roadbed by three feet and/or install a tide gate on the culvert under Chapaquoit Road. Alternatively, a slightly larger and lower culvert could be designed to provide a partial restoration of tides to the bay and prevent overtopping in flood events that don't overtop Chapaquoit Road. This option would be a cheaper alternative and would not require intensive management to prevent flooding of the road. It would also increase the intertidal area of Little Neck Bay by a factor of five, increase the tidal prism by a factor of eight, and decrease the residence time from six days to less than one day. Restoring partial tidal exchange should improve marsh and benthic habitat, but not completely restore it. The Town of Falmouth will have to determine the costs versus benefits of the two alternatives.

Tidal exchange to the Oyster Pond could be achieved by lowering the restrictive shoal upstream and replacing the present 3-ft diameter culvert with a 4 X 4-ft box culvert. This would increase tidal range and tidal prism by a factor of 2.5 and double the rate of flow through the culvert. Increasing the turnover time should improve marsh and intertidal habitat and improve marsh health.

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