SMAST
University of Massachusetts Dartmouth
The School for Marine Science and Technology

Technical Memorandum

DRAFT

Detailed Assessment of Water and Nutrient Exchange within the Quashnet River / Moonakis River Sub-embayment to Waquoit Bay

To:

Town of Falmouth
Water Quality Management Committee
Chair, Eric Turkington
and
Town of Mashpee
Mashpee Sewer Commission
Chair, Tom Fudala

From:

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Background:

The Waquoit Bay Estuary, also called the Waquoit Bay-Eel Pond Embayment System (after its major basins), is a complex system comprised of a main bay and associated tributary sub-embayments to both the east and the west. The Quashnet River, Hamblin Pond/Little River, and Jehu Pond/Great River are three major tributary sub-embayments to the Waquoit Bay System and are located along the eastern shore of the main basin. Eel Pond and the Childs River, which are connected to Waquoit Bay by the Seapit River, are large tributary sub-embayments to the Waquoit Bay System and are located along the western shore of the main bay (Figure 1). The three eastern shore sub-estuaries (Hamblin Pond, Jehu Pond and Quashnet River) were prioritized for initial assessment and threshold analysis by the DEP/SMAST Massachusetts Estuaries Project (MEP) to support on-going nitrogen management planning by the Town of Mashpee. The MEP nutrient threshold analysis for those three sub-embayments was completed in 2004 and the associated MassDEP TMDL was accepted by USEPA (2007). The 2004 MEP analysis was later reviewed in 2013 for linkage to the overall Waquoit Bay/Eel River/Childs River embayment system for TMDL development. The MEP found that the Quashnet/Moonakis River Estuary was nitrogen enriched and highly eutrophic, with impaired habitat for benthic animals and periodic large phytoplankton blooms and macroalgal accumulations. It was determined that the nitrogen enrichment was due to high watershed nitrogen loads and potentially reduced tidal exchange with waters from Waquoit Bay.

As with all other estuaries in the Town of Falmouth and across the southeastern Massachusetts region, the primary ecological threat to the estuarine resources of Waquoit Bay and its sub-embayments (Quashnet River, Hamblin Pond/Little River, Jehu Pond/Great River, Eel Pond, Childs River) is degradation resulting from nitrogen enrichment stemming from nitrogen inputs from land-uses within the watershed. Presently and at the time of the MEP nutrient threshold analysis for the Quashnet River / Moonakis River sub-embayment, data indicate that this sub-embayment continues to show signs of significant nutrient related habitat impairment. As summarized below by the MEP Technical Team.

The water quality indicators that are central to evaluating the nutrient related habitat health for eelgrass and benthic infaunal communities are the degree of oxygen depletion in bottom waters, the prevalence of macroalgae accumulations and the level of phytoplankton biomass (blooms) as determined from total chlorophyll-a measurements.

Based on the MEP analysis, the dissolved oxygen records for the tidally influenced lower Quashnet River indicated that this sub-embayment showed a high level of oxygen stress. Nitrogen enrichment of embayment waters can manifest itself in the dissolved oxygen record, both through oxygen depletion and through the magnitude of the daily excursion. This phenomenon was clearly seen in the Quashnet River record, where dissolved oxygen levels frequently became significantly depleted during the night and reached levels in excess of atmospheric saturation during the day time. From the oxygen records collected by the MEP, the Quashnet River has the greatest extent of oxygen depletion of all the eastern tributary sub-embayments to the overall Waquoit Bay. Additionally, the oxygen excursions indicated a high degree of nutrient enrichment (as also indicated by the chlorophyll-a data). It is important to note that these data were from the lower part of Quashnet River system, which would have the highest water quality. Even so, data still show the oxygen levels were <4 mg L^{-1} almost 10% of the time.

Based upon measured total chlorophyll-a pigments (sum of chlorophyll-a and its immediate breakdown product, pheophythin a, as a better indicator of bloom conditions) collected during the MEP analysis, it was clear that the Quashnet River was (and continues to be) a highly

Figure 1. Major components of the Waquoit Bay Estuarine System. The three major sub-embayments within the eastern portion of the Waquoit Bay System (Quashnet River, Hamblin Pond/Little River, Jehu Pond/Great River) were integrated in the nutrient threshold analysis of the broader Waquoit Bay system completed in March 2013. The Quashnet River received a detailed MEP threshold analysis previously in 2004-2005. Tidal waters from Nantucket Sound enter the main basin of Waquoit Bay through a single inlet in the barrier beach and a smaller inlet to the Eel Pond sub-embayment. Freshwaters enter the estuary primarily through two major surface water discharges (Childs River to Eel Pond and Quashnet River to the main Bay), several smaller streams (e.g. Red Brook), and direct groundwater discharge.

eutrophic system with total chlorophyll-a levels in the upper and mid regions averaging >20 ug L^{-1}. Chlorophyll-a values >10 ug L^{-1} typically indicate nitrogen enrichment. The moored chlorophyll sensor showed similarly high values. During the MEP data collection effort in the Quashnet River system, phytoplankton blooms appeared to be generated within the upper and mid basins of the Quashnet River, most likely as a result of the high nitrogen loading to the headwaters via the Quashnet River freshwater discharge. Exceedingly large blooms were observed within the upper Quashnet River basin (>140 ug L^{-1}), with very large blooms (>40 ug L^{-1}) also being observed in the mid reach of the estuary (bridge divides lower from mid reaches). Based upon all of the chlorophyll and oxygen data it appeared at the time of the MEP that the Quashnet River Estuary was showing oxygen stress throughout its reach and it is likely that the level of depletion was higher in the upper and mid reaches than in the lower basin, consistent with the distribution of phytoplankton biomass.

Observed signs of impairment seen in the benthic animal habitat indicators in the Quashnet River sub-embayment were consistent with the levels of oxygen depletion, chlorophyll-a and organic enrichment, including macroalgal accumulation. Benthic habitat assessment found only a single benthic animal species present, yielding aa diversity of 0. The severely degraded nature of this habitat is underscored by the virtual absence of an infaunal community with only 18, 4, and 0 individuals being found at the three sites sampled by the MEP, compared to 100's to 1000's being found at healthy sites in other systems.

Overall, the pattern of infaunal habitat quality throughout the Quashnet River - Moonakis River sub-embayment is consistent with measured dissolved oxygen concentrations, chlorophyll, nutrients and organic matter enrichment in this system (Table 1). Classification of habitat quality necessarily includes the structure of the specific estuarine basin, specifically as to whether a basin area is wetland influenced or an open water tidal embayment. Based upon the MEP analysis it was clear that most of the benthic animal habitat within the Quashnet River was severely degraded by nitrogen and organic matter enrichment. The proximate cause of the impairment was and continues to be organic matter enrichment and oxygen depletion, stemming ultimately from nitrogen enrichment from the watershed. As such the MEP developed a sub-embayment specific nutrient threshold for the Quashnet River which forms the basis for developing nutrient load reducing restoration solutions and the present detailed water and nutrient exchange assessment of the Quashnet-Moonakis River system.

Table 1. MEP Summary of Nutrient Related Habitat Health for the **Quashnet River**, Hamblin Pond/Little River and Jehu Pond/Great River sub-embayments to the Waquoit Bay System.

Health Indicator	**Eastern Sub-Embayments of the Waquoit Bay System**					
	Quashnet River		**Hamblin Pond/Little R.**		**Jehu Pond/Great R.**	
	Upper	**Lower**	**Hamblin Pond**	**Little River**	**Jehu Pond**	**Great River**
Dissolved Oxygen	SI	SI	MI	MI	SI	MI
Chlorophyll	SD	SI	MI	MI	MI/SI	MI
Macroalgae	SD	SD	--[2]	--[2]	--[2]	--[2]
Eelgrass	SI/SD	SI/SD[1]	MI	MI	MI	MI
Infaunal Animals	SD	SD	MI	H	SI	MI
Overall:	**SD**	**SI/SD**	**MI**	**H/MI**	**SI**	**MI**

1 – eelgrass lost prior to 1951; 2- sparse to no accumulation;
H = healthy habitat conditions; MI = Moderate Impairment; SI = Significant Impairment;
SD = Severe Degradation

The approach for determining nitrogen loading rates, which will maintain acceptable habitat quality throughout and embayment system, is to first identify a sentinel location within the embayment or sub-embayment and second, to determine the nitrogen concentration within the water column which will restore that location to the desired habitat quality. The sentinel location is selected such that the restoration of that one site will necessarily bring the other regions of the system to acceptable habitat quality levels. Once the sentinel site(s) and its target nitrogen level are determined, the Linked Watershed-Embayment Model is used to sequentially adjust nitrogen loads until the targeted nitrogen concentration is achieved.

In order to develop an appropriate threshold nutrient concentration that would be supportive of healthy habitat within the Quashnet River - Moonakis River sub-embayment, it was necessary to select a sentinel station at which nutrient concentrations would be monitored. The sentinel system within the Quashnet River Estuary was set within the upper/mid basin (region above the bridge). Achieving the nitrogen threshold at this station would also improve benthic habitat in the lower basin. Since there is no historical evidence that the Quashnet River Estuary has previously supported eelgrass, the threshold nitrogen concentration was based upon restoring benthic habitat at the sentinel station. The target MEP developed nitrogen concentration to restore infaunal habitat was based upon the high quality infaunal sites in the adjacent lower Hamblin Pond and in Little River (Stations 176 and 170). A conservative estimate for the infaunal threshold for the Quashnet River Estuary is 0.50 mg TN L^{-1}, with 0.52 likely to represent a slight stress, but still high quality habitat.

Introduction:

Since completion of the 2013 revision of the MEP analysis for the Quashnet River and its integration into the broader Waquoit Bay MEP assessment, the Mashpee Water Quality Monitoring Program, conducted as a collaboration between the Town of Mashpee, the Mashpee Wampanoag Tribe and the Coastal Systems Program (CSP-SMAST), has tracked continuing nutrient enrichment likely leading to further habitat decline within the Quashnet Estuary. The results confirm that this tributary embayment is still highly nitrogen enriched (possibly periodically also phosphorous impaired) and is supporting eutrophic conditions similar to those observed over the past decade (Overview of the 2010 Water Quality Monitoring Program for the Popponesset Bay and Waquoit Bay Estuaries, June 2011 as well as the report including the 2012 and 2013 seasons, dated June 2014).

All available data collected most recently by the Coastal Systems Program as well as historically under the MEP indicate that the one of the most nutrient enriched estuaries in Mashpee and Falmouth is the Quashnet River. This estuary is also one of the least saline, with salinities periodically declining to 1-2 PSU in the uppermost regions above the bridge, while salinity in the lower basin remains above 16 PSU compared to adjacent Waquoit Bay which is greater than 28 PSU. In addition, the upper basins appear to be getting fresher. In parallel with the fresher water are higher total nitrogen (TN) levels. and likely total phosphorous (TP) levels. In addition the monitoring data suggest that tidal flushing with the main basin of Waquoit Bay may be periodically being reduced decreasing the rate of salt water inflow and flushing out of nitrogen rich waters, while the freshwater inflow remains unchanged. The general effect is longer residence times and reduced flushing with lower nutrient saline waters resulting in very high TN levels, such as those observed. Additionally, recent changes in the up-gradient watershed, specifically the removal of a dam structure on the freshwater reach of the Quashnet River, may have altered the TN and TP loads to the lower reaches of the system through decreased natural attenuation. The MEP determined natural attenuation in the Quashnet River was upwards of 44 percent.

To address concerns presented above, the present follow-on detailed assessment of flows and nutrient exchange across the Quashnet - Moonakis River sub-system was undertaken to clarify:

1) the extent of tidal dampening and throughout the sub-estuary,
2) the locations of possible flow restrictions,
3) the potential increase in tidal flushing if restrictions are identified and remediated,
4) the degree to which the uppermost reaches of the system may need to be managed periodically for phosphorus, when the upper reach is dominated by freshwater,
5) the degree to which stream N and P loads have changed as a result of up-gradient modifications of dam structures changing nutrient dynamics and loading to the lower estuarine basins and
6) the degree to which propagation of shellfish in the Quashnet/Moonakis River could assist nutrient removal and contribute to improvements to water quality.

It should be noted that an associated problem would be increased particle settling in the upper estuarine reach increasing organic matter loading to the sediments. Increased particle settling generally increases the frequency of low oxygen events through increased oxygen demand, while water column nutrient enrichment is enhanced through increased rates of N and P release from sediments. To elucidate these various points, a comprehensive field data collection effort was undertaken to further refine understanding of the continued poor water/habitat quality in the Quashnet/Moonakis River sub-embayment to the overall Waquoit Bay Estuary and specifically how it might be remediated to restore the lost estuarine habitat (cf. MEP Nutrient Reports).

Since the MEP analyses there have changes to the River. One example is the dam removal from the freshwater reach of the Quashnet River upgradient of Route 28. The removal of the dam likely has altered sediment and nutrient transport to the down-river estuarine reaches. Additionally, altered sedimentation in the lower estuarine reach may be decreasing tidal exchange and flushing of the Quashnet River sub-estuary with Waquoit Bay waters. Beyond quantifying the effect of changes that have occurred in the system, equally important was the need to investigate the potential for “soft” solutions to lower nitrogen levels within the lower estuarine basins and Waquoit Bay, which was outside of the focus of the MEP analysis. Addressing these “gaps” for nutrient management planning is the focus of the present effort, which will build on both the MEP and the Water Quality Monitoring Program.

This Technical Memorandum is structured to mirror the Scope of Work (SOW) submitted to the Town of Falmouth/Mashpee and summarizes the work completed for each Task described in the SOW as follows:

Task 1. Hydrodynamic Field Data Collection.
    A. Tide Data (Stage) Collection
    B. Review Available Bathymetric Data and Collection of Additional Data on Areas of Shoaling or Constriction

Task 2. Tidal Flux Determination for Exchange between the upper and middle Quashnet basins and the lower basin (below the bridge)

Task 3. Confirmation of Flow, Total Nitrogen and Phosphorus in freshwater discharge from the Quashnet River to the estuarine tidal reaches

Task 4. Benthic Nutrient Flux (input/output)

Task 5. Assessment of Habitat Suitability for Shellfish Propagation

This project was completed as a partnership between the Towns of Mashpee and Falmouth and the Coastal Systems Program (CSP) within the University of Massachusetts-Dartmouth (UMD), School for Marine Science and Technology (SMAST). The CSP provided technical direction, data collection and sample analysis; the Town of Mashpee undertook outreach and education regarding the project. Previous water quality data collected by the joint Town/Tribe water quality monitoring program, in collaboration with the CSP, was incorporated into the overall study as appropriate. The work to be undertaken for the overall assessment and study of nitrogen and phosphorous management options (enhanced flushing and suitability of shellfish aquaculture) in the Quashnet sub-embaryment was initiated in the spring of 2016 upon contract execution with the majority of the field work being undertaken through the summer months (June, July, August) when environmental conditions the critical period for estuarine management. Field data collection was focused on the entire Quashnet sub-embayment (Figure 2), but particularly the area up-gradient of the Meadow Neck Road bridge crossing to create detail on key hydrodynamic factors controlling flow and nitrogen deposition/release.

The Towns of Mashpee and Falmouth are currently engaged in pursuing a myriad of nitrogen management options in order to reduce the amount of nutrients going into the waters of the Quashnet Estuary as well as the receiving waters of Waquoit Bay. Managing the amount of nitrogen contributed to the Quashnet / Moonakis River from its watershed as well as managing the effect of the nitrogen (and possibly phosphorus) on the receiving waters will not only reduce the impairment of the sub-embayment, but also improve the quality of the water discharging to the greater Waquoit Bay ecosystem. Therefore, nutrient management in the Quashnet / Moonakis River serves as a means of helping the Towns achieve their nitrogen TMDL threshold for the Waquoit Bay Estuary, as the Quashnet Estuary is a net exporter of nutrients to the Bay. Based on the MEP Linked Watershed-Embayment Nitrogen Threshold Analysis, within the Waquoit Bay estuary, to prevent further loss of eelgrass habitat and to restore eelgrass to 1951 and 1995 levels, tidally averaged TN at the long-term water quality station in the bay, WB-12, needs to be lowered to 0.38 mg L^{-1}. Given the historic absence of eelgrass in the estuarine waters of the Quashnet / Moonakis River, improving habitat and water quality is focused on restoring the benthic animal communities that are the base of the estuarine food chain. Restoring the health of the Quashnet / Moonakis River will enhance the habitat quality for river fish populations, which in turn serve to support numerous bird and mammal species.

Multiple options for restoring the Quashnet/Moonakis River Estuary are being considered, including (a) the potential for enhanced tidal exchange, (b) in estuary nitrogen management through aquaculture, and (c) watershed source reductions. The present study is to examine the potential for options (a) and (b). Once a plan for nitrogen reduction within this tributary to Waquoit Bay is developed, its impact on the Quashnet Estuary and the entire Waquoit Bay estuary should be assessed using the existing MEP Linked Model for Waquoit Bay.

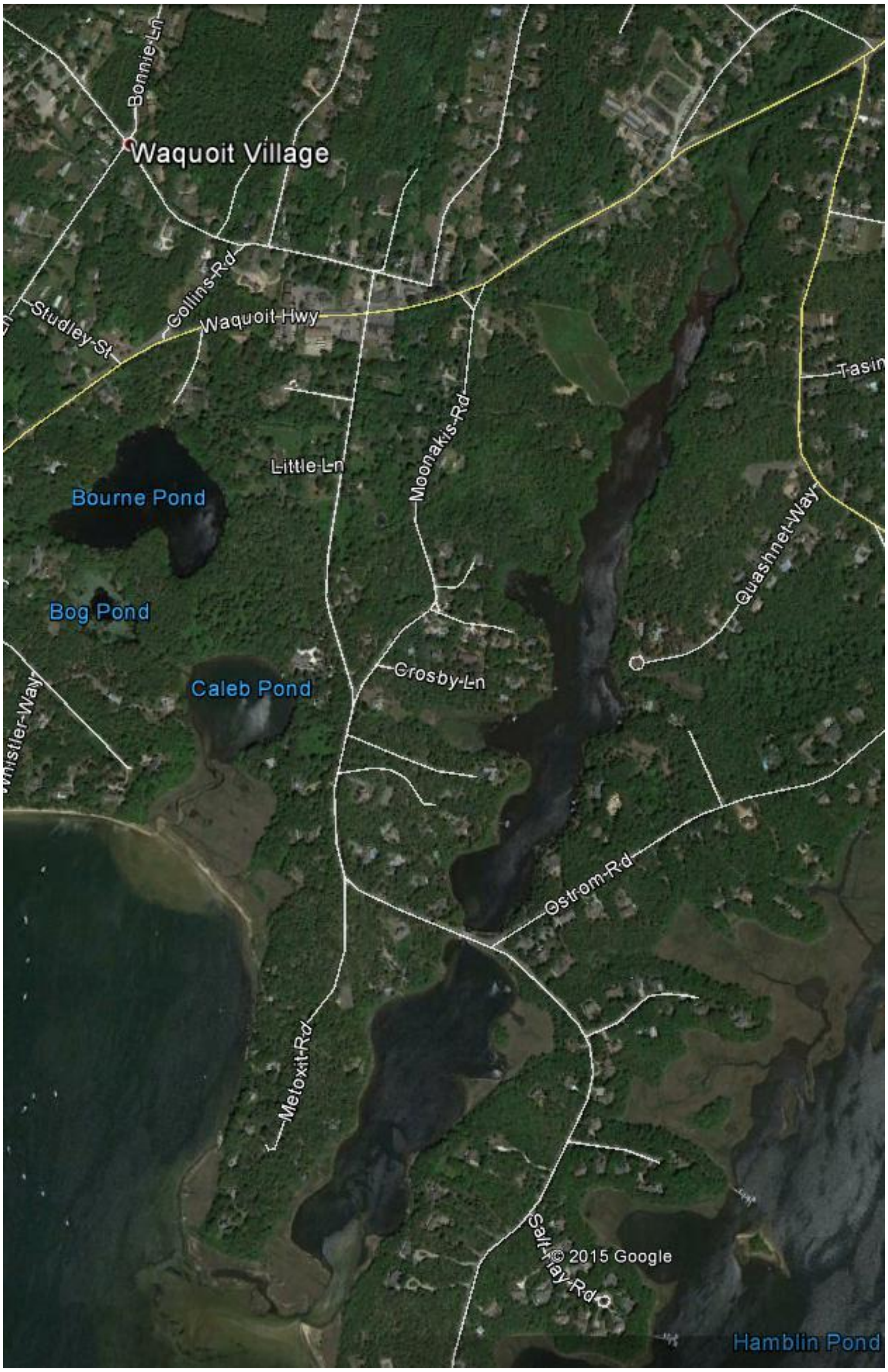

Figure 2. Quashnet / Moonakis River study area in the Towns of Falmouth and Mashpee, MA. Field data collection was be undertaken in both the upper and lower portions of the system as demarcated by the Meadow Neck Road bridge crossing.

Hydrodynamics and Tidal Flushing:

To test the feasibility of a flushing enhancement due to changes post-MEP analysis and the extent of improvement that might be obtained, hydrodynamic field data collection focused on the entire Quashnet Estuary but particularly the tidal inlet (connecting the lower portion of the Quashnet River to the main body of Waquoit Bay) and the area up-gradient of the Meadow Neck Road bridge crossing. This effort generated detail on key hydrodynamic factors (tidal stage and bathymetry) controlling flow and nitrogen deposition/release. Critical to being able to complete an updated assessment of the flushing characteristics of the Quashnet / Moonakis River Estuary is having an accurate measure of the volume of water in the sub-embayment over time as well as the degree of tidal damping across the sub-embayment through the inlet of the system to its head. To that end CSP scientists deployed four (4) tide gages in the Quashnet / Moonakis River sub-estuary as well as one (1) "offshore" gage in the main basin of Waquoit Bay (driving tide) to obtain a fine scale record of tidal stage over at least one complete lunar cycle. Additionally, a updated bathymetric survey was completed to clarify potential areas of shoaling across the system as well as determine a revised system volume. All of these metrics were compared to MEP measurements in an attempt to quantify any changes that may have occurred in tidal flushing over the past 14 years.

A. Tide Data (Stage) Collection

Water level loggers (Global Waters WL-16) were deployed at five locations throughout the Quashnet / Moonakis River system (Figure 3). The gages were deployed on June 23, 2016 and recorded tidal stage until October 2016 covering multiple lunar cycles (28 days) in order to measure changing water levels at critical junctures in the Quashnet/Moonakis River and adjacent Waquoit Bay. The only exception was the Moonakis Lower gage which failed in August 2016. Nonetheless all gages functioned simultaneously for more than the minimum required 1 complete lunar cycle (Figure 4). Comparing the Waquoit Bay tide range to water levels in the lower Quashnet basin allowed CSP scientists to assess the potential restriction of the tidal inlet. In addition, the positioning of gages at various locations below and above the Meadow Neck road bridge provided an evaluation of any potential restriction posed by the new bridge or between the 3 gauges in the upper basins (Moonakis lower, mid and upper). The tidal stage data was collected in parallel with the high resolution bathymetry which clarified physical structures (shoals or bars), which have been suggested to be limiting flushing of high nutrient concentration water out of the system.

Precise knowledge of time-series tidal elevation within the system was required to understand the flushing characteristics of the system and determine if it might be possible for enhancement. As the tide rises in the Waquoit Bay estuary, water floods into the Quashnet / Moonakis River Estuary and is distributed through to the upper portions of the sub-embayment above Meadow Neck Road. Characteristics of the sub-embayment system, such as depth, and bottom roughness (friction), distort the tidal wave as it travels through the system from inlet to headwaters. Tidal distortion may include a reduction in the range of the tide (damping) and/or a delay in the time of occurrence of low and high tides. It is the extent of tidal damping through the system that affects the volume exchange, and hence the flushing characteristics, between Waquoit Bay and the estuarine reaches of the Quashnet River.

Figure 3. Water level loggers deployed in the Quashnet / Moonakis River study area in the Towns of Falmouth and Mashpee, MA. as well as the "offshore" gage located in the main basin of Waquoit Bay.

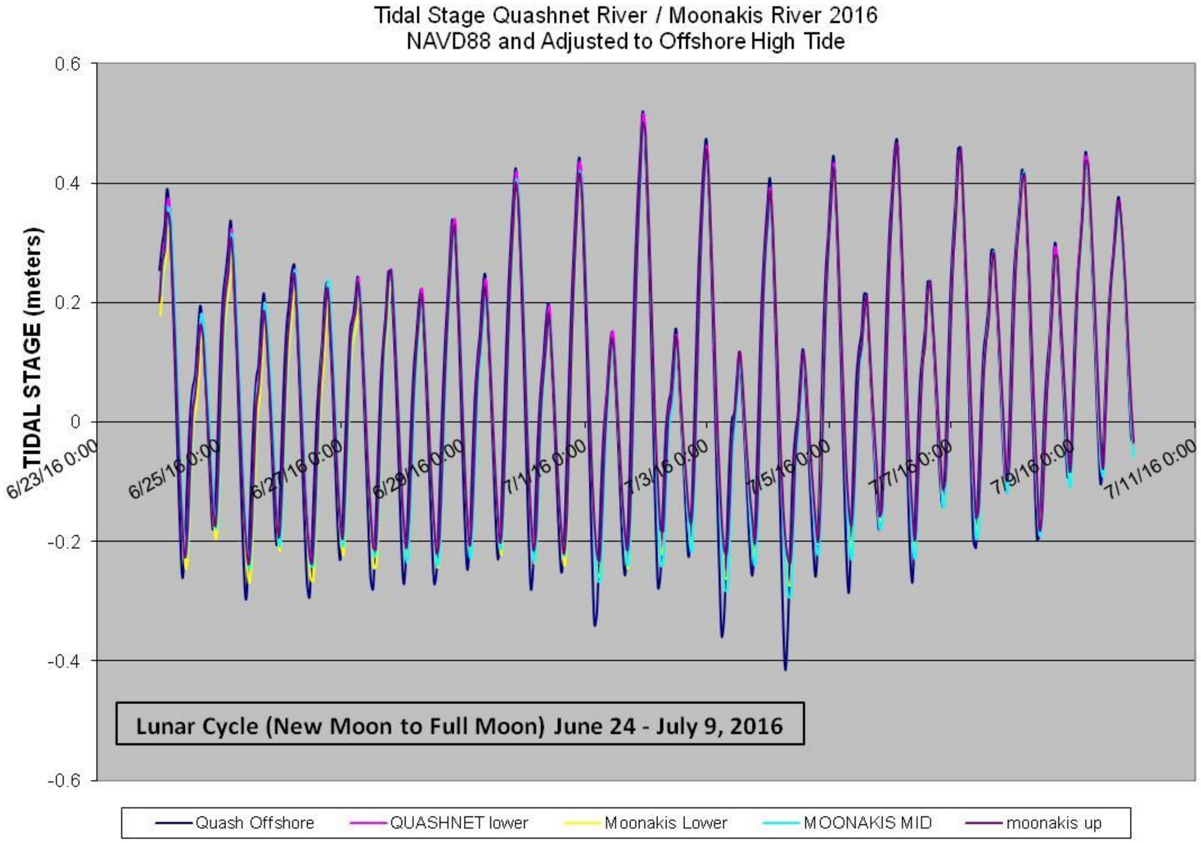

Figure 4. Tidal stage record for 1 lunar cycle (new moon to full moon, June 24 - July 9 2016) from all five gages deployed in Waquoit Bay and the Quashnet / Moonakis River system.

The Quashnet / Moonakis sub-embayment's forcing tide, or the "offshore" tide, in the Waquoit Bay main basin was measured using a tide gage deployed on a pier adjacent Waquoit Landing Road across the bay from the inlet to the Quashnet River Estuary. Within the Quashnet / Moonakis River basin, four tide gauges were installed on piers along the length of the system. One gage (Quashnet Lower) was deployed in the lower basin (below Meadow Neck Road Bridge) and the three remaining gages (Moonakis Lower, Mid and Upper) were all located above the bridge such that the gages did not go dry during the lowest low tide of the lunar cycle. Accurate measurement of the forcing tide ("offshore") was critical because it provides the basis for evaluating flushing characteristics within the system as well as quantification of the exchange (tidal flux) of water between Waquoit Bay and the Quashnet River, during a given tidal cycle. The vertical elevation of each tide gage was measured relative to a common vertical datum (NAVD88) and then further cross referenced to offshore gage. This enabled direct comparison of one tidal record to another. Potential restrictions to tidal flow were revealed through collection of these tidal stage data sets with the two main constrictions of concern being: 1) the inlet connecting the lower Quashnet River basin to Waquoit Bay and 2) the channel passing under the Meadow Neck Road bridge connecting the lower Quashnet River to Moonakis River basin.

Plots of short portions (3-4 days) of the overall tidal stage record collected at each gage were developed (Figures 5,6,7) in order to more clearly show the relative relationships between the tidal stage records within the Quashnet River / Moonakis River system and the tide stage in Waquoit Bay (offshore). Generally, there was little difference (0-5cm) between the tide stage record collected from the "offshore" gage in Waquoit Bay compared to the tide gage in the lower portion of the Quashnet River. However, as the intensity of the tide varies across the lunar cycle, there were times during the tide gage deployment period when the difference between the offshore gage and the Quashnet Lower gage was greater (max. difference was 19cm {7.29in.}). However, almost all of the reduction in tidal range inside versus outside of the Quashnet Estuary was due to higher low tides inside versus outside. This is typical of small tributary systems (and salt marshes) where the deeper basin offshore can support a lower low tide due mainly to bathymetry and not a tidal restriction. Tidal restrictions are primarily seen in reductions in the high tide elevation moving from offshore to inshore gauges, which is not the case in this system. Specifically, the tide records obtained from four gages within the Quashnet-lower basin, Moonakis-lower,mid,upper basins show negligible damping of the tide stage (i.e. reach same high tide levels), although the low tide mark is slightly higher than the offshore gauge in all cases. As such, it does not seem likely modifying the channel at Meadow Neck Road would enhance exchange of water between the lower and upper parts of the Quashnet Estuary, although dredging of the shoal may increase the tidal range to the extent that a lower low tide can be achieved.

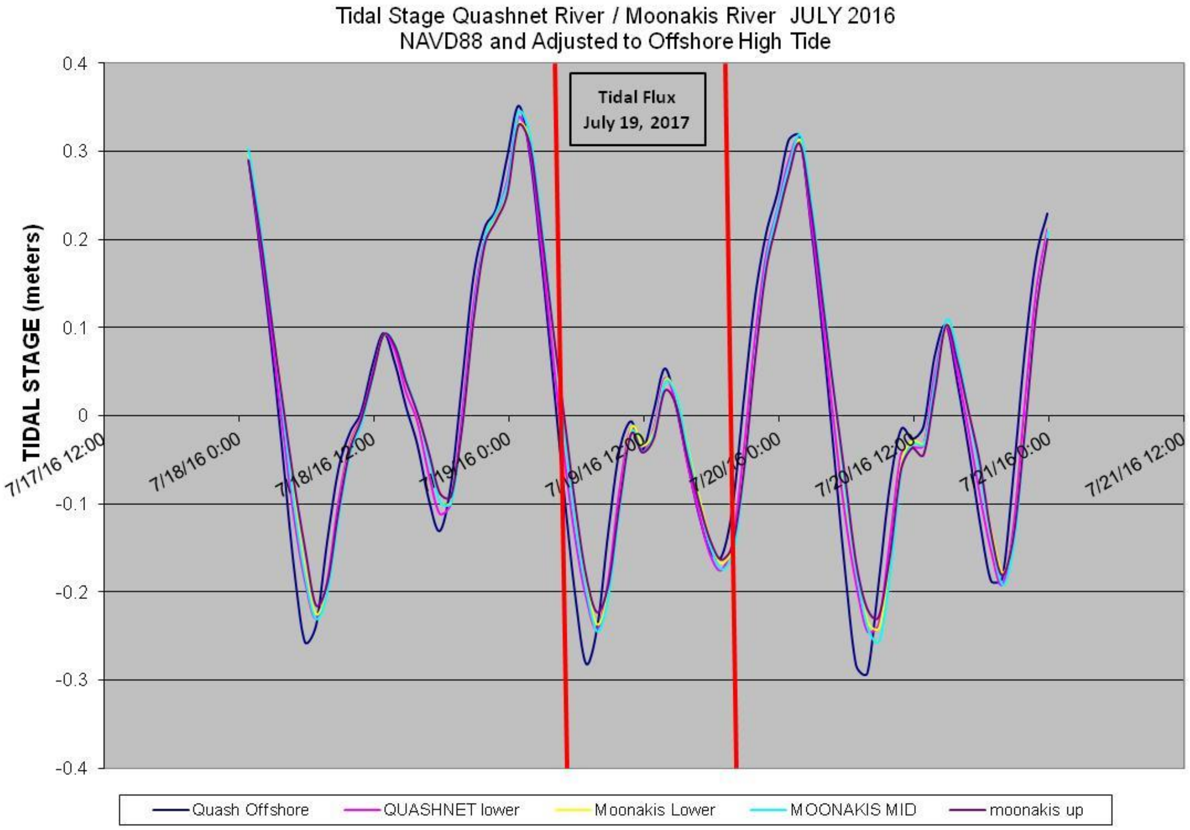

Figure 5. July 2016 tidal stage record with Tidal Flux 1 (7/19/16) demarcated by red lines.

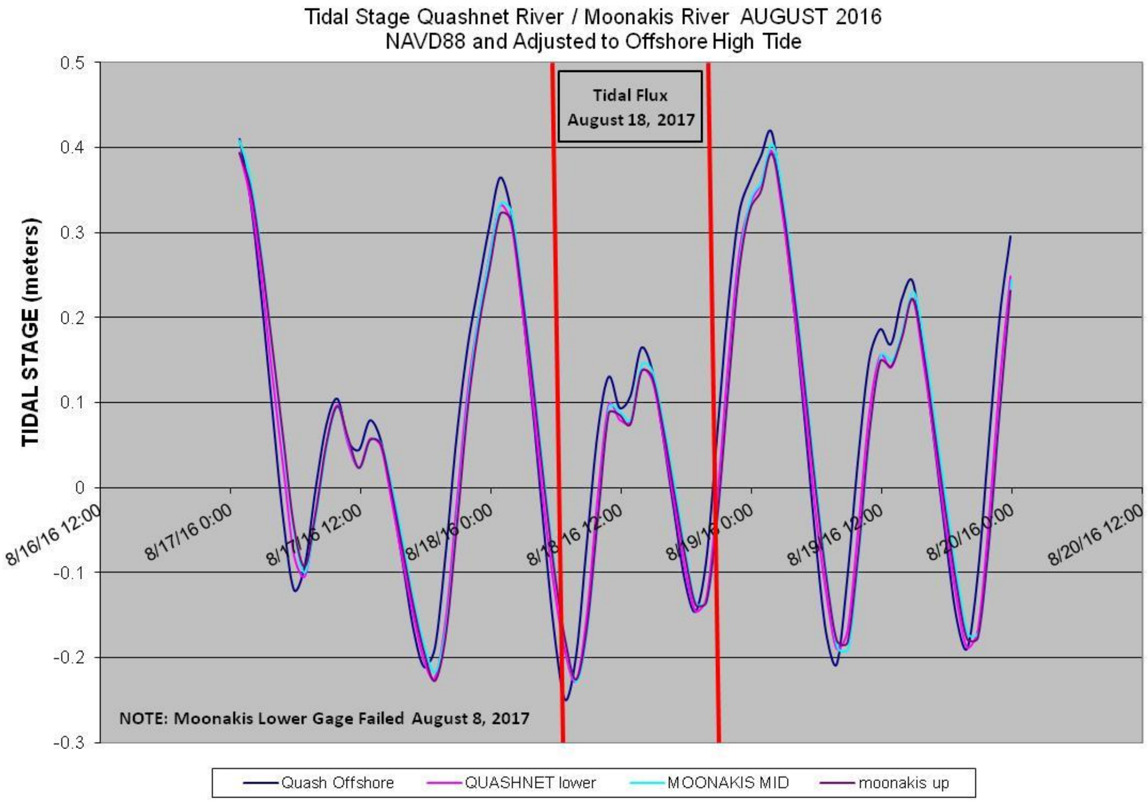

Figure 6. August 2016 tidal stage record with Tidal Flux 2 (8/18/16) demarcated by red lines.

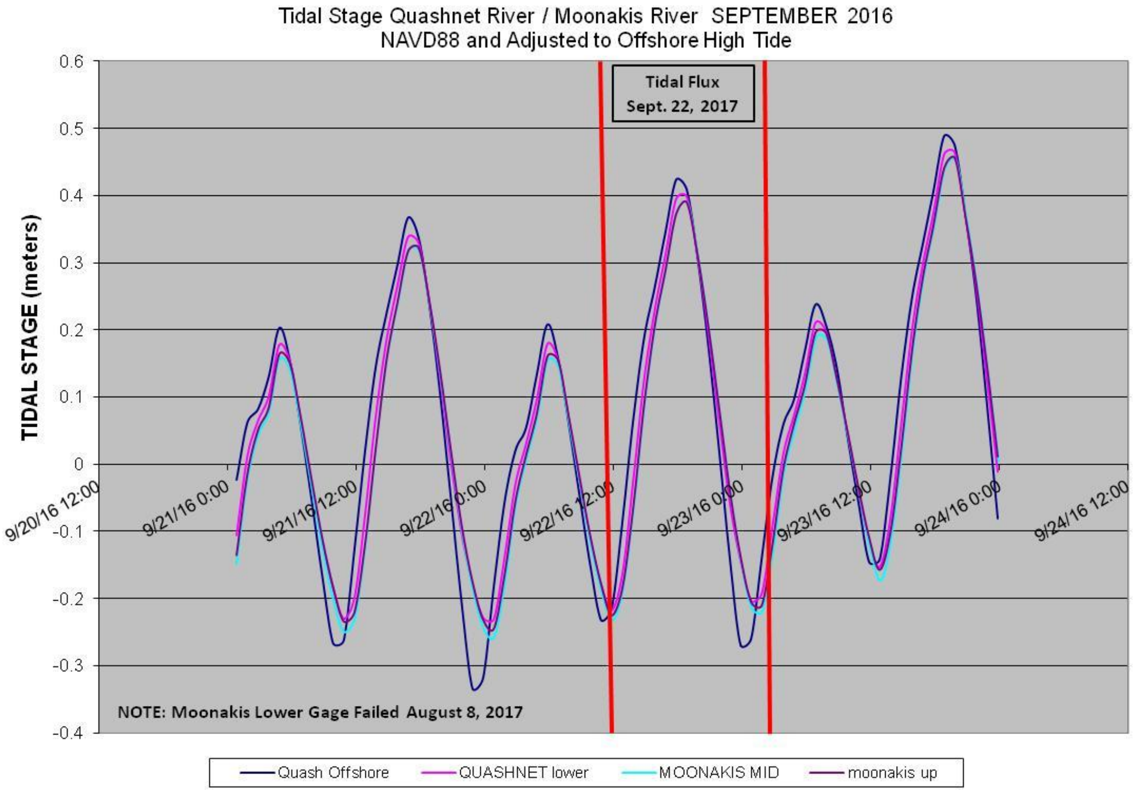

Figure 7. September 2016 tidal stage record with Tidal Flux 3 (9/22/16) demarcated by red lines.

B. Review Available Bathymetric Data and Collection of Additional Data on Areas of Shoaling or Constriction

A refined bathymetric survey was completed building on the survey completed for the 2004 and 2013 MEP analysis of the Quashnet River and Waquoit Bay respectively. The original 2002 bathymetry survey (Figure 8, left panel) was completed as the basis of the MEP hydrodynamic model. The updated bathymetric survey completed in 2016 (Figure 8, right panel) was to determine if any shoals, barriers or basins have formed over the past 10 years thereby representing depositional areas and possibly sites of organic matter accumulations where recycling of nitrogen from the sediments is enhanced. The refined bathymetry also enabled the determination of sites that might be managed so as to restore tidal flushing. Based on the 2002 bathymetric survey, it is clear that shoaling is occurring at the tidal inlet connecting the Quashnet River to the main basin of Waquoit Bay. Equally important, it also shows that the constriction at the Meadow Neck Road bridge crossing is defined by a deep scoured channel. In both the recent surveys and 2002 MEP analysis, there did not appear to be any large restrictions or significant dampening of the tide as it propagates the length of the Quashnet / Moonakis River sub-embayment. However, during the MEP analysis there were not sufficient gages deployed the length of the system to fully confirm the lack of tidal dampening.

To determine the volume of Quashnet / Moonakis River sub-embayment and gain a refined understanding of flushing restrictions and water residence time, the collection of depth data (bathymetry) in the region of the tidal inlet and throughout the sub-embayment was completed while tide gauges were collecting tidal stage data. As such, the depth measurements could be referenced to the local instantaneous water level; the local water level at all locations within the system were then referenced to a common vertical datum (NGVD29, consistent with the historic MEP analysis) using water level measurements recorded by the tide gauges (i.e., tide-corrected bathymetry measurements) and a mean tide level (Tables 2a,b).

In 2016, an updated bathymetry map of the Quashnet River / Moonakis River system was completed using the same surveying protocols employed during the MEP analysis and depth data referenced to a similar datum (NGVD29). Both the 2002 and the 2016 bathymetric surveys indicate shoaling at the inlet of the Quashnet River, scouring at the narrow channel passing under the Meadow Neck Road bridge and significant shallow water in the upper reaches of the system. It does not appear the bathymetry of the system has changed significantly in that the calculated system volume based on the 2016 survey is within 1.7% of that determined by the MEP during its nutrient threshold analysis, well within measurement error (Tables 2a & b).

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Table 2a. Quashnet River / Moonakis River system basin volumes, areas tide ranges and tidal prism based on updated bathymetry and tide date collection completed in June-October 2016. Upper corresponds to Moonakis-lower,mid,upper tide gage records while lower corresponds to Quashnet-lower tide gage records (** based on NOAA tide prediction tables January to December 2016).

<table>
<tr><th colspan="6">Quashnet River Estuary</th></tr>
<tr><td colspan="6">Area and Volume Estimates Based on 2016 Bathymetry (Boundary at Bridge)</td></tr>
<tr><td colspan="6">Volume (ft^3)</td></tr>
<tr><td colspan="2">Upper</td><td colspan="2">Lower</td><td colspan="2">Total</td></tr>
<tr><td colspan="2">4,425,952</td><td colspan="2">6,797,967</td><td colspan="2">8,988,131</td></tr>
<tr><td colspan="6">Surface Areas (ft^2)</td></tr>
<tr><td colspan="2">Upper</td><td colspan="2">Lower</td><td colspan="2">Total</td></tr>
<tr><td colspan="2">866,538</td><td colspan="2">1,088,985</td><td colspan="2">1,955,512</td></tr>
<tr><td colspan="6">Tide Range (ft)</td></tr>
<tr><td colspan="3">Winter</td><td colspan="3">Summer</td></tr>
<tr><td colspan="3">1.43**</td><td colspan="3">1.78</td></tr>
<tr><td colspan="6">Tidal Prism (ft^3)</td></tr>
<tr><td colspan="3">2,796,382</td><td colspan="3">3,480,811</td></tr>
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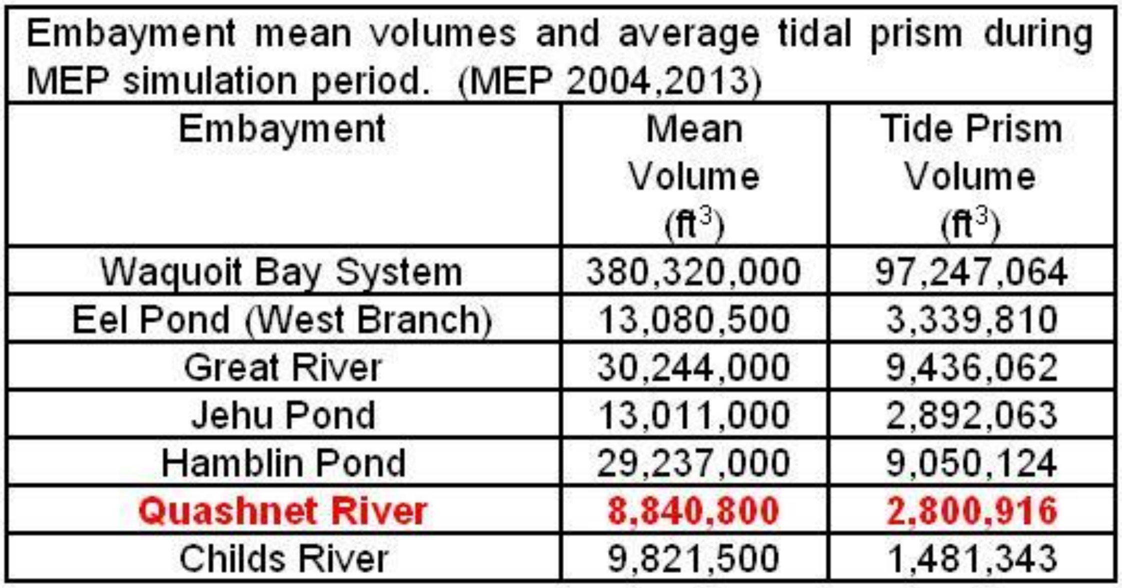
Table 2b. Quashnet River / Moonakis River system basin volumes and tide prism volumes based on bathymetry and hydrodynamic data collection and modeling completed in 2002-2004 for the Massachusetts Estuaries Project nutrient threshold analysis. Data collection took place in January 2002, so that the tidal prism represents winter conditions.



Embayment mean volumes and average tidal prism during MEP simulation period. (MEP 2004,2013)

Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)
Waquoit Bay System	380,320,000	97,247,064
Eel Pond (West Branch)	13,080,500	3,339,810
Great River	30,244,000	9,436,062
Jehu Pond	13,011,000	2,892,063
Hamblin Pond	29,237,000	9,050,124
Quashnet River	**8,840,800**	**2,800,916**
Childs River	9,821,500	1,481,343

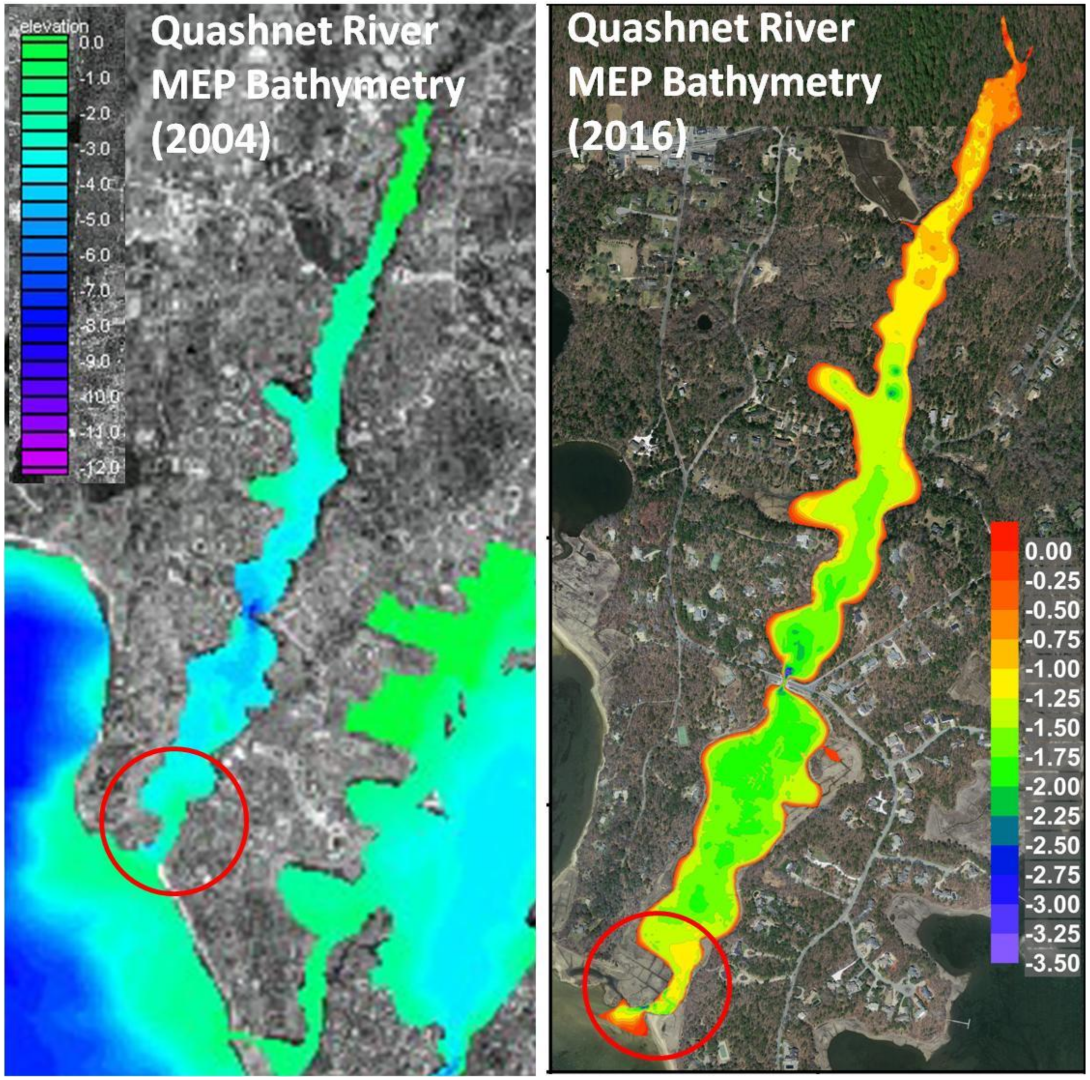
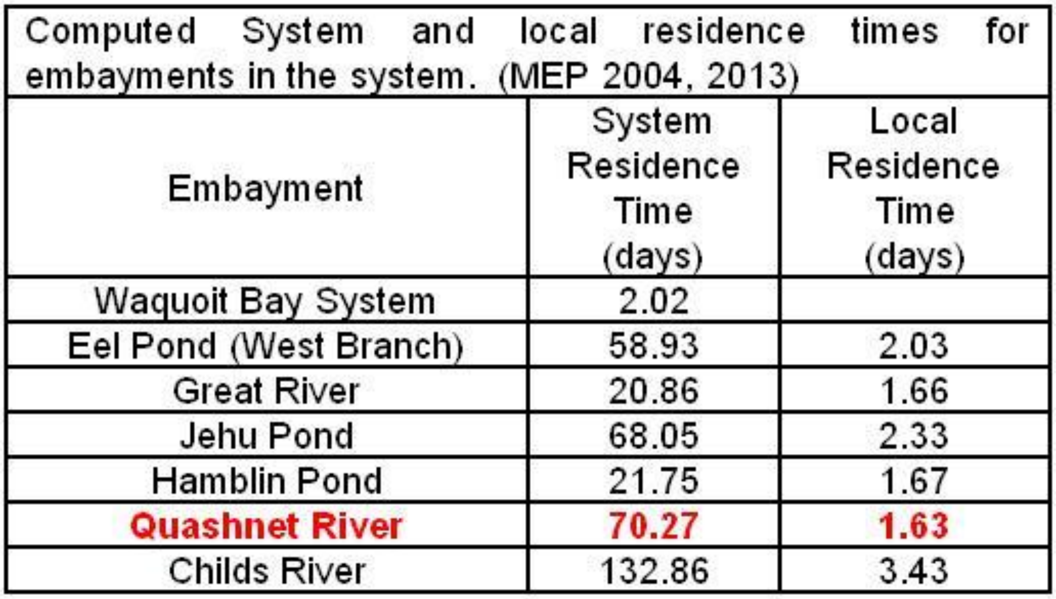


Figure 8. Quashnet River bathymetric survey completed in 2002 and utilized by the Massachusetts Estuaries Project (left panel) for flushing and water residence time analysis compared to bathymetric survey completed in 2016 (right panel). Red circles highlights clear areas of shoaling at the tidal inlet connecting Quashnet River to Waquoit Bay. Constriction at Meadow Neck Road bridge shows a deep scoured channel in both surveys.

While the system volume based on the 2016 bathymetric survey is slightly higher than that which was calculated by the MEP, the two volumes are essentially the same showing only <2% difference over the 10+ years that have elapsed since the Quashnet River was first evaluated by the MEP. Moreover, making the comparison in terms of local residence time of water in the Quashnet River system as determined by the MEP analysis (Table 3) vs. in 2016, there is no significant difference in the flushing of the system. Using the same tidal prism as was determined by the MEP, (79,313m^3 or 2,800,916 ft^3) and the new volume determined based on the 2016 bathymetry survey, the local residence time for the Quashnet River / Moonakis River system in 2016 was consistent with the MEP analysis, 1.67 days compared to 1.63 days in 2002. More significant to the rate of nutrient export for the Quashnet Estuary, the tidal prism (the volume of water entering and leaving over a tidal cycle was also found to be unchanged from the MEP, 2,800,916 ft^3 per tide versus 2,796,382 ft^3 per tide in 2016, only a 0,2% difference. It appears that there has been little structural change within the Quashnet Estuary basin that would have change tidal dynamics since 2001.

Table 3. Quashnet River / Moonakis River system system and local residence times based on bathymetry and hydrodynamic data collection and modeling completed in 2002-2004 for the Massachusetts Estuaries Project nutrient threshold analysis.



Computed System and local residence times for embayments in the system. (MEP 2004, 2013)

Embayment	System Residence Time (days)	Local Residence Time (days)
Waquoit Bay System	2.02	
Eel Pond (West Branch)	58.93	2.03
Great River	20.86	1.66
Jehu Pond	68.05	2.33
Hamblin Pond	21.75	1.67
Quashnet River	**70.27**	**1.63**
Childs River	132.86	3.43

Tidal Flux Determination for Exchange between Quashnet Lower and Moonakis:

Measurements of tidal inflow and outflow through the channel connecting the upper Quashnet River (aka. Moonakis River) to the lower portion of the Quashnet River estuary were undertaken to provide direct measurements of tidal volume exchange as well as to estimate residence time of water in the sub-embayment. Two tidal nutrient flux events were completed (July, August) at the Meadow Neck Road bridge crossing in order to quantify the flow into and out of the Moonakis River as well as the associated changes in nitrogen and salinity concentrations over a complete tidal cycle (low to high to low). The flow results were merged with the water quality records of total nitrogen and salinity to calculate the net transport of water, salt and nutrients from the upper portion of the system to the lower section.

Each sampling took place over a single complete tidal cycle beginning approximately 1 hour before low tide and ending approximately 1 hour after the following low tide (Figures 9,10).

Before each tidal flux, precipitation amounts were monitored for at least 3 days prior to the first sampling to ensure that water and nutrient flux data would not be biased by rain-related flows. Precipitation >0.25” is used to designate a significant precipitation event. Water samples were collected in the channel at the Meadow Neck Road bridge at approximately hourly intervals over the course of the tidal cycle. Samples were analyzed for temperature, pH, salinity, chlorophyll-a, inorganic phosphorus and total nitrogen, comprised of ammonium, nitrate/nitrite, Dissolved Organic Nitrogen (DON), and Particulate Organic Nitrogen (PON). Flood and ebb current velocity measurements and channel cross-section water depths were made concurrently with water sample collection in the channel outflow/inflow to determine volumetric flow through the channel (Meadow Neck Road bridge crossing) during both flood and ebb tides. These flow data were then utilized to quantify total volumetric flow into and out of this portion of the sub-embayment. Total flow into Moonakis River was calculated between slack low tide and slack high tide. Total flow out was calculated from slack high tide to the point at which the tidal height during ebb reached the same level as that recorded at the previous slack low tide, as measured by staff gauges deployed up-gradient (in the Moonakis River) and down-gradient (in the lower Quashnet River) estuary.

Volumetric exchange during flood and ebb tides was used to calculate the mass flux of salt and nutrients into and out of the Moonakis River on each of the 2 sampling dates. Data from each collected water sample was paired with the corresponding flow rate to calculate a mass flux of each constituent for each time point during the tidal cycle which is integrated over the tidal cycle to yield the total mass flux (i.e. the total out minus the total in = net flux). From these tidal exchange data, the magnitude and direction of the net flux of water and nutrients was calculated (Table 4a).

Table 4a. Summary of flood and ebb tide volumes and total nitrogen loads for each of the tidal flux experiment (July, August) all adjusted to the flood tide salinity and points of equal stage.

Flux Event	Date	Flood Volume	Ebb Volume	**Net FLOW**	Flood Load	Ebb Load	**Net LOAD**
		(m^3)	(m^3)	**(+) in (-) out**	(kg-TN)	(kg-TN)	**(+) in (-) out**
Tidal Flux 1	7/19/16	21833	34573	**-12740**	28.95	37.51	**-8.56**
Tidal Flux 2	8/18/16	20793	28080	**-7287**	24.89	41.97	**-17.08**

Generally, there was a net export of water from the Moonakis River to the lower basin of the Quashnet Estuary (and then to Waquoit Bay). This results from freshwater from the watershed being added to the volume of water within the basins above the bridge prior to it flowing out on the ebb tide. The effect is that there is more water in the outflow (but fresher) than on the inflow (saltier). In addition, based upon the results of the two tidal flux experiments, it appears that there is a net export of total nitrogen load to Waquoit Bay from the Quashnet / Moonakis River system.

Results of Tidal Flux Experiment 1 - July 19, 2016

Tidal flux experiment 1 was completed on a spring tide (full moon), July 19. Tidal stage was measured simultaneously in the river above and below the Meadow Neck Road bridge crossing where velocity measurements and sampling took place (Figure 9a). The tide stage records were not adjusted to a common datum as they were only used to determine relative changes in stage and to determine timing of high and low tide (slack) and give a context for the volumetric flow and nitrogen load in (flood +) and out (ebb -) of the river through the bridge opening. Comparing the stage records from above and below the Meadow Neck Road bridge, it appears there is little to no temporal lag or attenuation in tide range resulting from the bridge opening. As the system floods, a gradual increase in salinity was observed with a corresponding decrease in salinity as the tide turns, begins to ebb and the influence of the freshwater from the Quashnet River becomes evident.

The influx of moderately higher quality water from Waquoit Bay during the flood tide is seen in the chlorophyll-a (CHLA) and total nitrogen (TN) concentrations of samples collected during the flood tide (Figures 9b and 9c). As salinity increases (representative of the water flowing into the Quashnet River / Moonakis River system from Waquoit Bay), there is a decrease in both the CHLA and TN concentrations. Conversely, as salinity drops during the ebb tide (representative of water discharging from the lower Moonakis River) both CHLA and TN concentrations increase significantly representative of the impaired water quality in the middle and upper reaches of the Quashnet / Moonaskis River system. The completion of flow and water quality measurements during a complete tidal cycle (flood through ebb) further confirmed that the Quashnet / Moonakis River generally acts as an exporter of lower quality, high nutrient (flood TN load = 28.95 kg, ebb TN load = 37.51 kg) water to the Waquoit Bay estuary (Table 4b). Given the nearly equal duration of the flood tide compared to the ebb tide and the magnitude of the freshwater entering the system from the watershed via groundwater and the large surface-water flow entering at the head of the estuary, a greater volume of water was measured on the ebb tide (outflow) with associated higher nutrient load when compared to the load that enters the system on the flood tide from the main basin of Waquoit Bay.

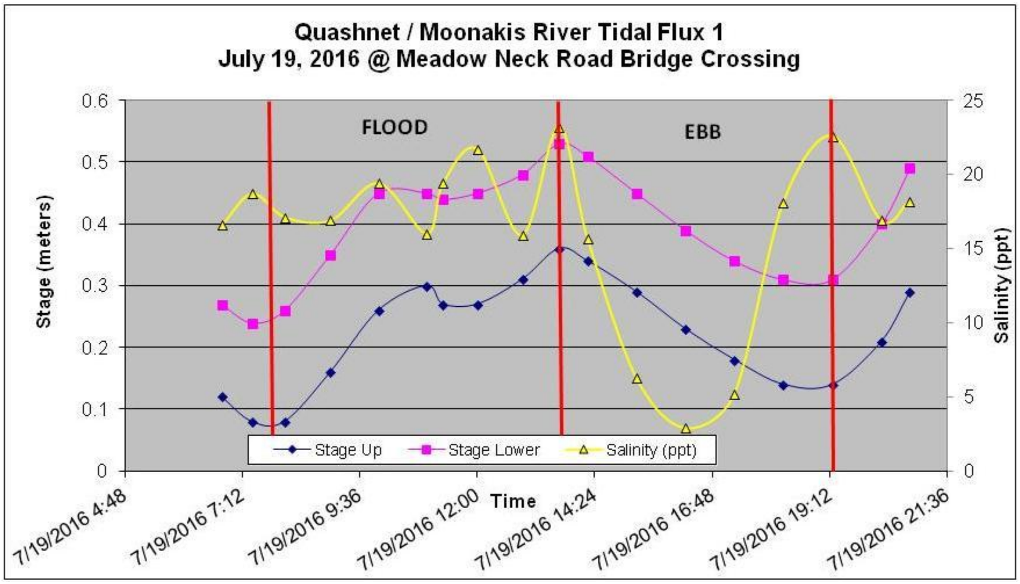


Figure 9a. Quashnet River tidal flux experiment 1 (July 2016) to quantify volumetric and nutrient mass exchange between the lower portion of the Quashnet River and the Moonakis River above Meadow Neck Road.

Table 4b. Summary of flow and nutrient fluxes during tidal flux experiment 1, July 19, 2016. Flood is represented by (+) values and ebb is represented by (-) values. Tidal exchange results in net export of freshwater and nutrients to the lower Quashnet Basin and Waquoit Bay from the upper and mid basins of the Quashnet/Moonakis Estuary.

Tidal Cycle	PO4 (load)	NH4 (load)	Nox (load)	DIN (load)	DON (load)	TDN (load)	POC (load)	PON (load)	C/N (load)	TON (load)	TN (load)
FLOOD Flux	**0.524**	**0.181**	**0.078**	**0.259**	**12.247**	**12.506**	**91.997**	**16.444**	**--**	**28.691**	**28.950**
EBB Flux	-0.99	-0.64	-0.34	-0.98	-16.24	-17.22	-119.28	-20.29	--	-36.53	-37.51
NET Flux	-0.464	-0.464	-0.259	-0.723	-3.995	-4.717	-27.279	-3.847	--	-7.841	-8.564

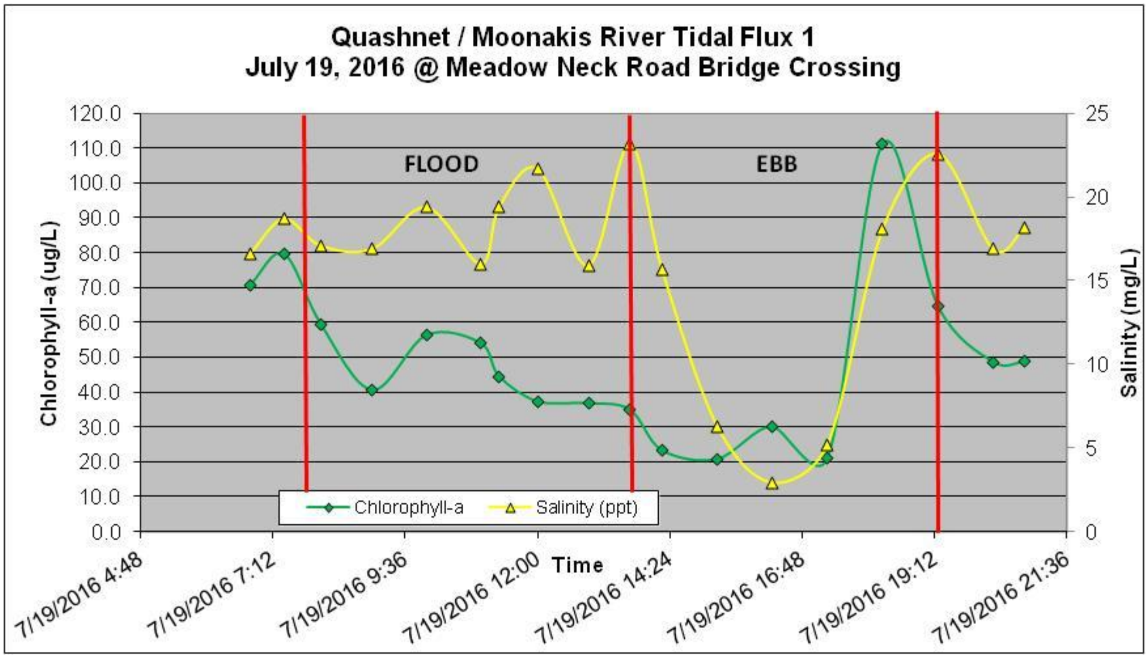


Figure 9b. Quashnet River tidal flux experiment 1 (July 2016) showing the changes in salinity and chlorophyll-a (CHLA) concentrations over both the flood and ebb tide as water exchanges between the lower portion of the Quashnet River and the Moonakis River above Meadow Neck Road.

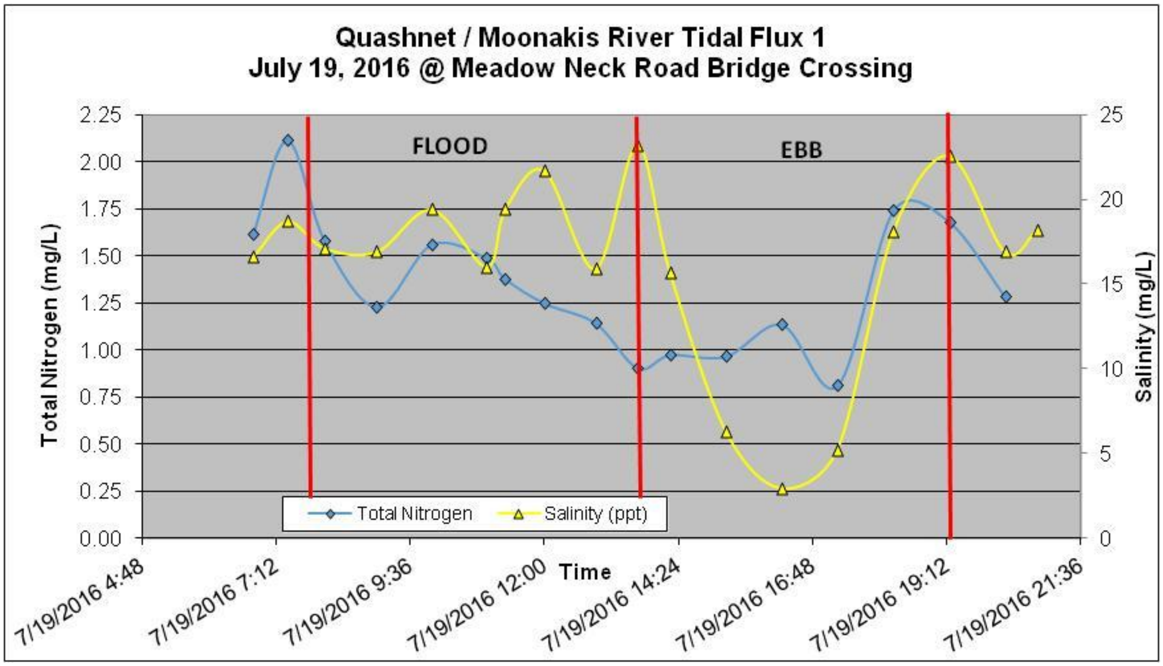


Figure 9c. Quashnet River tidal flux experiment 1 (July 2016) showing the changes in salinity and Total Nitrogen (TN) concentrations over both the flood and ebb tide as water exchanges between the lower portion of the Quashnet River and the Moonakis River above Meadow Neck Road.

Results of Tidal Flux Experiment 2 - August 18, 2016

As with tidal flux experiment 1, tidal flux experiment 2 was also completed on a spring tide (full moon), August 18. For comparability of results, similar procedures were followed during the August flux as for the July flux. Tidal stage was measured simultaneously in the river above and below the Meadow Neck Road bridge crossing where velocity measurements and sampling took place (Figure 10a) to determine the degree of lag and damping of the tide as it propagates up the river (magnitude of stage difference) and how that corresponds to volumetric flow and nitrogen load in (flood +) and out (ebb -) of the river. As was observed in July, there was little to no attenuation of the tide range, as seen in the relative stage records from above and below the Meadow Neck Road bridge. As the system floods, a gradual increase in salinity was observed with a corresponding decrease in salinity as the tide reverses and begins to ebb and the influence of the freshwater from the Quashnet River becomes evident.

The influx of moderately higher quality water from Waquoit Bay during the flood tide was again seen in the chlorophyll-a (CHLA) and total nitrogen (TN) concentrations during the flood tide (Figures 10b and 10c). As salinity increases (representative of the water flowing into the Quashnet River / Moonakis River system from Waquoit Bay), there is a decrease in both the CHLA and TN concentrations. Conversely, as salinity drops during the ebb tide (representative of water leaving Quashnet / Moonakis River) both CHLA and TN concentrations increase as the nitrogen enriched waters of the middle and upper reaches of the Quashnet / Moonskis River system flow out. However, unlike tidal flux (1), CHLA and TN levels measured on both the flood and ebb tide showed more variability. Even so, the completion of flow and water quality measurements over the complete tidal cycle (flood through ebb) confirmed that the Quashnet / Moonakis River generally acts as an exporter of lower quality, high nutrient (flood TN load = 24.89 kg, ebb TN load = 41.97 kg) water to the Waquoit Bay estuary (Table 4c). In tidal flux (2), net TN export was greater than TN export from tidal flux (1), 17.08 kg vs. 8.56 kg respectively. The difference is attributable to the higher observed flood and ebb TN concentrations during tidal flux (2) compared to tidal flux (1) possibly due to seasonal release of nitrogen from senescing plants and organic matter decomposition.

Similar to the July tidal study, the August results also had nearly equal duration of the flood tide and ebb tide and the magnitude of the freshwater entering the system from the watershed via groundwater and the large surface- water flow entering at the head of the estuary, a greater volume of water was measured on the ebb tide (outflow) with associated higher nutrient load when compared to the load that enters the system on the flood tide from the main basin of Waquoit Bay. Given the nearly equal duration of the flood tide compared to the ebb tide and the magnitude of the freshwater entering the system from the watershed via groundwater and the large surface- water flow entering at the head of the estuary, a greater volume of water was measured on the ebb tide (outflow) with associated higher nutrient load when compared to the load that enters the system on the flood tide from the main basin of Waquoit Bay. Given the nearly equal duration of the flood tide compared to the ebb tide and the magnitude of the freshwater entering the system from the watershed via groundwater and the large surface-water flow entering at the head of the estuary, a greater volume of water was measured on the ebb tide (outflow) with associated higher nutrient load when compared to the load that enters the system on the flood tide from the main basin of Waquoit Bay.

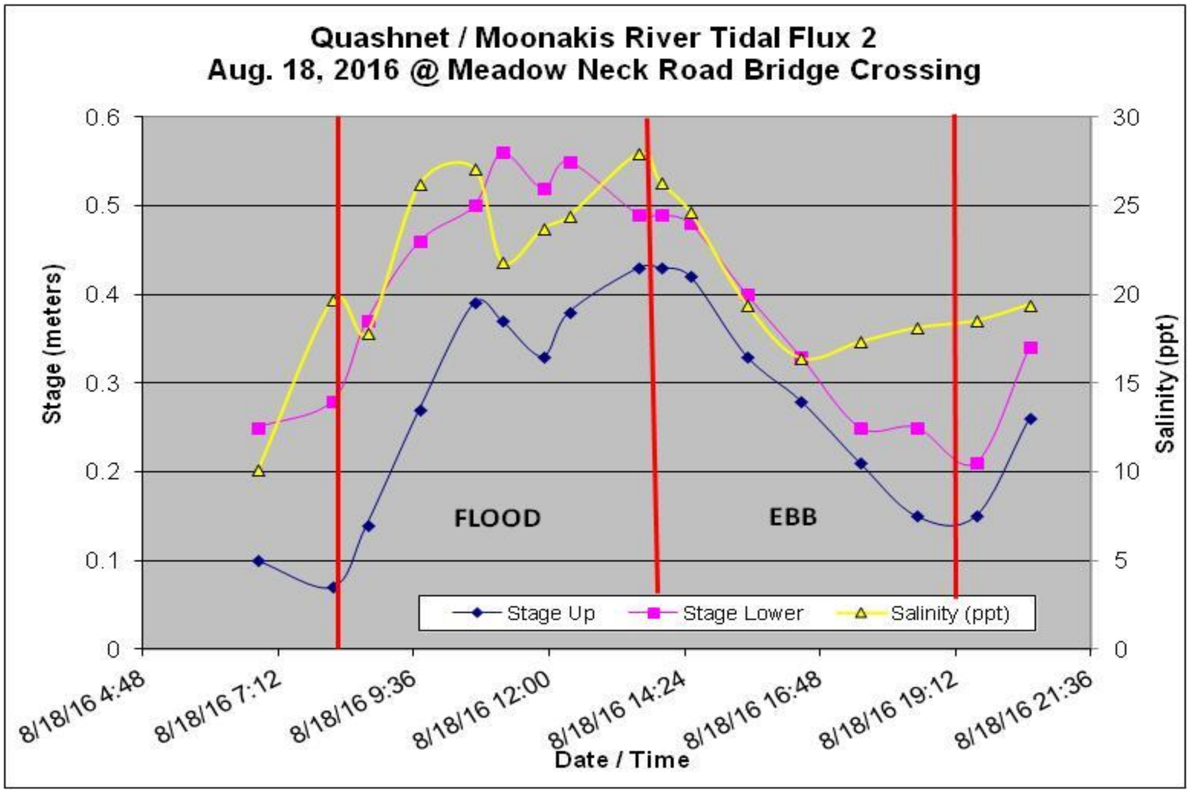


Figure 10a. Quashnet River tidal flux experiment 2 (August 2016) to quantify volumetric and nutrient mass exchange between the lower portion of the Quashnet River and the Moonakis River above Meadow Neck Road. Tide stages are relative but show similar ranges and temporal maxima.

Table 4c. Summary of flow and nutrient fluxes during tidal flux experiment 2, August 18, 2016. Flood is represented by (+) values and ebb is represented by (-) values. Tidal exchange results in net export of freshwater and nutrients to the lower Quashnet Basin and Waquoit Bay from the upper and mid basins of the Quashnet/Moonakis Estuary.

Tidal Cycle	PO4 (load)	NH4 (load)	Nox (load)	DIN (load)	DON (load)	TDN (load)	POC (load)	PON (load)	C/N	TON (load)	TN (load)
FLOOD Flux	**0.77**	**0.15**	**0.04**	**0.19**	**9.08**	**9.27**	**91.93**	**15.62**	**--**	**24.70**	**24.89**
EBB Flux	-0.90	-0.41	-0.07	-0.48	-16.13	-16.61	-168.29	-25.36	--	-41.49	-41.97
NET Flux	-0.14	-0.26	-0.03	-0.29	-7.05	-7.34	-76.36	-9.74	--	-16.79	-17.08

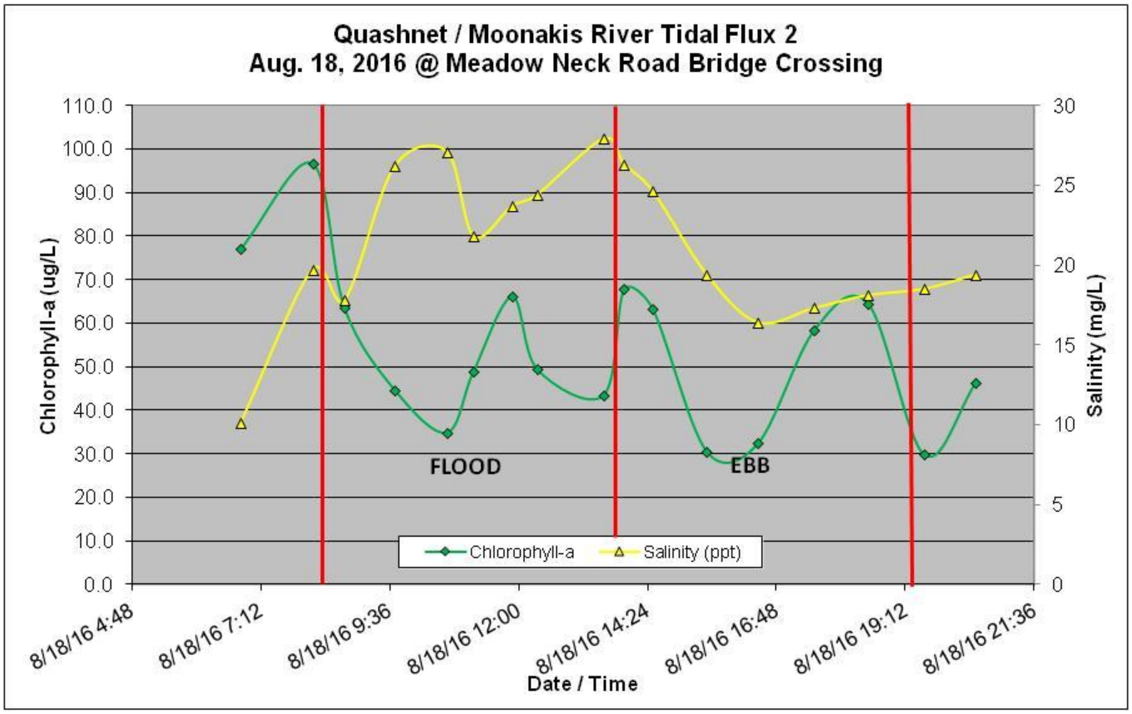


Figure 10b. Quashnet River tidal flux experiment 2 (August 2016) showing the changes in salinity and chlorophyll-a (CHLA) concentrations over both the flood and ebb tide as water exchanges between the lower portion of the Quashnet River and the Moonakis River above Meadow Neck Road.

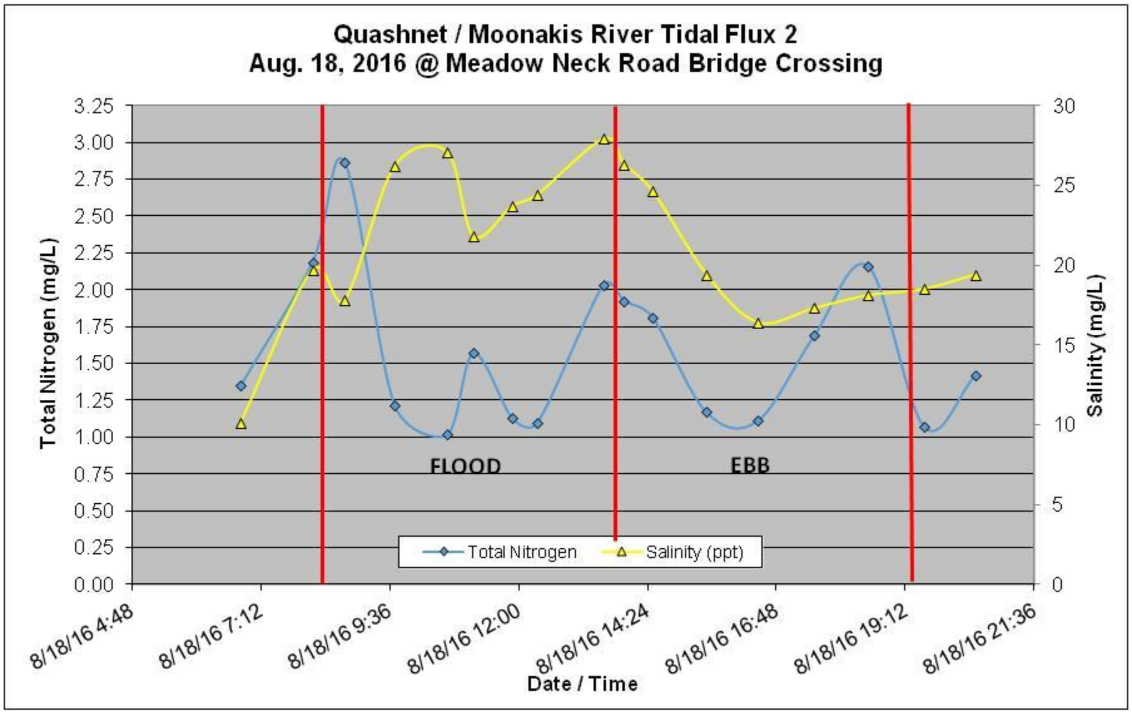


Figure 10c. Quashnet River tidal flux experiment 2 showing the changes in salinity and Total Nitrogen (TN) concentrations over both the flood and ebb tide as water exchanges between the lower portion of the Quashnet River and the Moonakis River above Meadow Neck Road.

Confirmation of Flow, Total Nitrogen and Phosphorus in Freshwater Discharge from the Quashnet River (Input to the Estuary)

As a result of modifications to a berm separating the Quashnet Bogs (head of the Quashnet River) from discharging directly to the River, the present nitrogen load entering the sub-embayment from this surfacewater system was evaluated.

Flow data from the USGS Quashnet River gaging station (011058837, Figure 11) was compiled for the study period (July - December 2016) and compared to flows determined for the same period by the MEP in 2003 in order to determine the flow volume and whether the nitrogen load into the Moonakis River has changed. Weekly water quality samples were collected by the CSP science team during the six (6) month period capturing the summer and fall such that nitrogen concentration data could be paired with flow data from the USGS in order to calculate Nitrate+Nitrite (NO_x), Total Nitrogen (TN) and Orthophosphate (PO_4) loads entering the estuary from this freshwater pathway. The 2016 load was compared to previous work undertaken by the MEP to determine the change in loading from the Quashnet River (Tables 5a,b).

Based on the USGS determined flows (July-December, Figure 12) for the long term gaging station (USGS 011058837 QUASHNET RIVER AT WAQUOIT VILLAGE, MA) located

Figure 11. USGS Gaging Station 011058837 on the freshwater portion of the Quashnet River up-gradient of Route 28 which discharges to the estuarine waters of the Quashnet/Moonakiss River below Route 28.

immediately up-gradient of Route 28, it appears that average daily flow in the six month period of this 2016 study was comparable to average daily flow determined at the same location during the MEP field data collection effort completed in 2003 (29,843 m^3/d and 30,540 m^3/d respectively). This similarity in the average daily flows allows for a more direct comparison of nutrient concentrations and loads in the Quashnet River following manipulation of the berm along river, which previously existed during the MEP stream gaging and nutrient loading effort.

Based on the weekly water quality monitoring undertaken by the CSP at the USGS gaging station on the Quashnet River, it was possible to determine average nutrient concentrations and loads for July through December 2016. As presented in the tables below, while 2016 and 2003 MEP average daily flows were essentially the same, NO_x and TN average daily concentrations were slightly higher in 2016. TN loads in 2016 and 2003 were 15.80 kg/d and 14.49 kg/d respectively, while NOx load was 7.82 kg/d and 5.99 kg/d respectively. These data indicate a 31% increase in NO_x load and a 9% increase in TN load in 2016 versus 2003 at the same average flow over the same 6 months of the year.

It should be noted that in the 1999-2000 time frame, a earthen berm was constructed separating a network of cranberry bogs from the Quashnet River in the uppermost reaches of the system close to the headwaters east of Johns Pond. Within a year of the berm being built, a portion of the berm failed that separated the K6 cell of the cranberry bog from the river (personal communication September 2017 with Mr. Andrew McManus, Town of Mashpee Conservation Agent). The breach has evolved over the years likely having varying degrees of effect on the flow in that portion of the upper Quashnet River depending on the magnitude of the hydrologic year (e.g. above average, average, below average flow). Interestingly, NO_x concentrations in the Quashnet River appeared higher in 2016 (16 years post breach) compared to 2003 which was close to the time of the initial berm failure (0.26 mg/L and 0.20 mg/L respectively). This may be as result of a lessening of the natural transformation and attenuation of NO_x thru biological activity that typically converts the highly bio-available NOx to organic nitrogen forms or dinitrogen gas. As generally found biologically active systems, TN also showed higher concentrations and loads but of lower magnitude (9% increase versus 31% increase) due to its inclusion of both inorganic and organic nitrogen forms. Unlike NO_x and TN, PO_4 load appeared to drop significantly from 2003 to 2016 (0.47 kg/d and 0.23 kg/d respectively). As flows in 2016 and 2003 were similar, the drop in PO_4 load resulted from a decrease in the measured PO4 concentration, 0.014 mg/L in 2003 versus 0.008 mg/L in 2016. At present the cause of these loading changes is unclear, but a closer examination of the alterations to the berm in the upper watershed may provide some of the answer, particularly as relates to the increased nitrogen load.

Overall, it appears that there has been an increase in nitrogen load discharged from the Quashnet River to the estuarine waters since the initial analysis in 2003. The most likely cause is a combination of increased watershed loading and/or alteration of the berm separating the cranberry bogs from the river. Whatever the cause, the trend toward increase nitrogen loading is consistent with the continuing degradation of nutrient related water and habitat quality within the Quashnet/Moonakis River Estuary. Additionally, should hydrologic conditions change in the Quashnet River itself due to alterations of flow rate and water residence time, this too can have positive or negative effects on nutrient loading to the estuarine portions of the system depending on the type of modification. As such it is still important to manage the watershed carefully to avoid unintentional increase of N and P loads to the down stream Quashnet River / Moonakis River estuary.

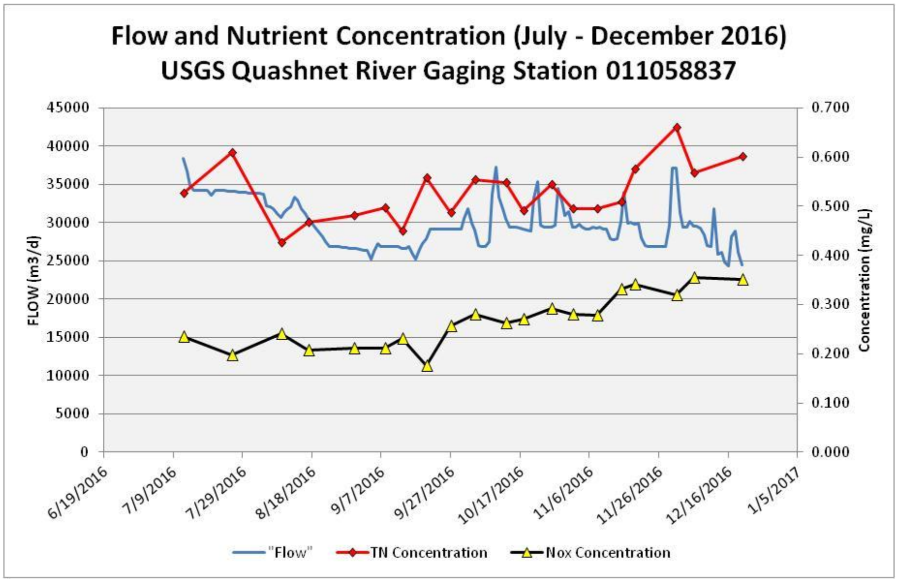


Figure 12. USGS average daily flows from the long term gaging station 011058837 up-gradient of Route 28. Flow is shown relative to Nitrate+Nitrite (NOx) and Total Nitrogen (TN) concentrations for near weekly stream samples collected by the CSP.

Table 5a. Summary of 2003 and 2016 Nitrate+Nitrite (NO_x), Total Nitrogen (TN) and Orthophosphate (PO_4) concentrations in the Quashnet River at the USGS gaging station (011058837).

Avg. Conc. (2003)	**Nox (uM)**	**Nox (mg/L)**	**TN (uM)**	**TN (mg/L)**	**PO4 (uM)**	**PO4 (mg/L)**
July	12.023	0.1683	31.969	0.448	0.382	0.0118
August	9.880	0.1383	33.651	0.471	0.659	0.0204
September	6.009	0.0841	31.431	0.440	0.358	0.0111
October	18.612	0.2606	39.337	0.551	0.277	0.0086
November	16.230	0.2272	36.567	0.512	0.393	0.0122
December	22.472	0.3146	40.585	0.568	0.626	0.0194
Avg. July-Dec.	**14.20**	**0.20**	**35.59**	**0.50**	**0.449**	**0.0139**

Avg. Conc. (2016)	**Nox (uM)**	**Nox (mg/L)**	**TN (uM)**	**TN (mg/L)**	**PO4 (uM)**	**PO4 (mg/L)**
July	15.452	0.216	40.551	0.568	0.221	0.0068
August	15.709	0.220	32.720	0.458	0.223	0.0069
September	15.606	0.218	35.574	0.498	0.223	0.0069
October	19.744	0.276	38.173	0.534	0.328	0.0102
November	22.001	0.308	37.016	0.518	0.257	0.0080
December	24.450	0.342	43.516	0.609	0.245	0.0076
Avg. July-Dec.	**18.83**	**0.26**	**37.92**	**0.53**	**0.249**	**0.0077**

Table 5b. Summary of 2003 and 2016 average daily flow July thru December as well as Nitrate+Nitrite (NO_x), Total Nitrogen (TN) and orthophosphate (PO_4) average daily load in the Quashnet River at the USGS gaging station (011058837).

	AVERAGE DAILY FLOWS AND LOADS											
Months	MEP Flow (2002-2003)	USGS Flow (2002-2003)	USGS Flow (2016)	Nox Load (MEP)	Nox Load (USGS)	Nox Load (2016)	TN Load (MEP)	TN Load (USGS)	TN Load (2016)	PO4 Load (MEP)	PO4 Load (USGS)	PO4 Load (2016)
July-Dec.	**30540**	**33286**	**29843**	**5.99**	**6.59**	**7.82**	**14.49**	**15.79**	**15.80**	**0.47**	**0.51**	**0.23**

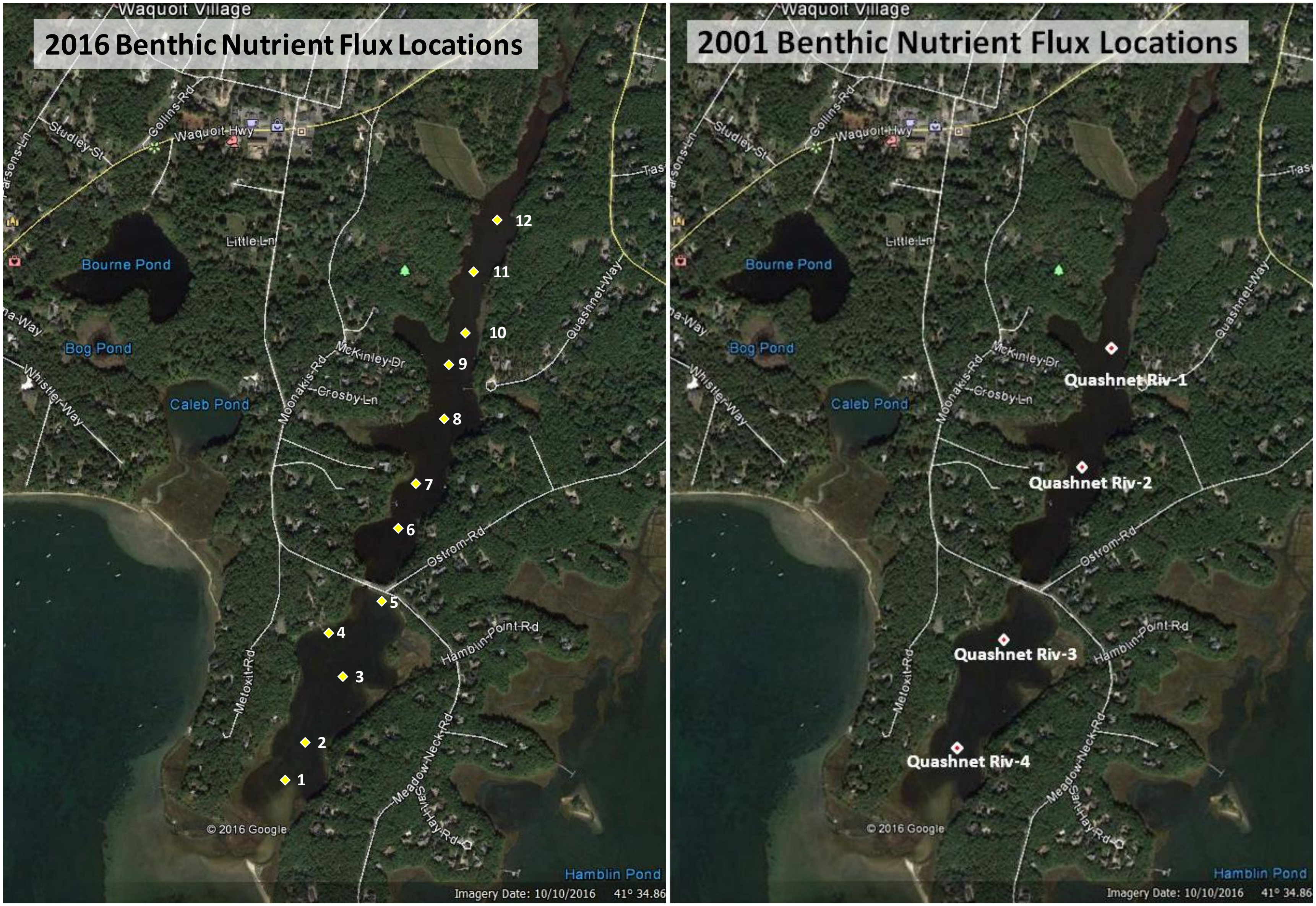
Benthic Nutrient Flux (input/output):

In addition to “new” nutrients (nitrogen or phosphorous) entering the sub-embayment estuary from the surrounding watershed, nitrogen is recycled within the sediments and water column. This recycled nitrogen adds directly to the eutrophication of the estuarine waters in the same fashion as watershed inputs. In some systems investigated by the MEP, recycled nitrogen can account for upwards of half the nitrogen supply to phytoplankton blooms during the warmer summer months. It is during these warmer months that estuarine waters are most sensitive to nitrogen and phosphorous loadings. Failure to account for this recycled nitrogen generally results in significant errors in quantifying the nutrient dynamics of a systems as well as determining the assimilative capacity (threshold) of the system thus impeding the development of effective management plans. Moreover, as there was a hydrologic manipulation (construction and later breaching of a berm) in the up-gradient watershed to the freshwater portion of the Quashnet River, it was important to re-evaluate the nutrient release / uptakes rates from the estuarine sediments to determine if there has been a significant change in that recycled load from 2001 to 2016.

The overall objective of the 2016 benthic nutrient flux effort was to quantify the summertime exchange of nitrogen between the sediments and overlying waters at a higher spatial resolution than what was completed for use in the MEP assessment (2001), but in a consistent manner such that net uptake and/or release of nutrients to the water column could be cross compared across the entire system. The mass exchange of nitrogen between water column and sediments is a fundamental factor in controlling nitrogen levels within coastal waters and when considered in the context of reduced circulation can have a significant effect on water column nutrient concentrations and habitat health. These fluxes and their associated biogeochemical pools relate directly to carbon, nutrient and oxygen dynamics and the nutrient related ecological health of shallow marine ecosystems such as the Quasnet / Moonakis River system.

As was undertaken under the 2001 assessment effort used in the MEP, in order to determine the contribution of sediment regeneration to nutrient levels in the Quashnet River / Moonakis River sub-embayment, sediment samples were collected and incubated under in situ conditions. Sediment samples were collected, during the most sensitive summer interval (July-August), from 12 sites (Figure 13) in 2016. The four (4) core locations evaluated under the MEP were revisited in 2016. Measurements of total dissolved nitrogen, nitrate + nitrite, ammonium were made in time-series on each incubated core sample. Rates of nitrogen release were determined using undisturbed sediment cores incubated for 24 hours in temperature-controlled baths. Sediment cores (15 cm inside diameter) were collected by SCUBA divers and cores transported by a small boat. Cores were maintained from collection through incubation at in situ temperatures. Bottom water was collected and filtered from each core site to replace the headspace water of the flux cores prior to incubation. Sampling was distributed throughout the sub-embayment and the results for each site combined for calculating the net nitrogen regeneration rates for the upper, middle and lower portions of the system.

Sediment-water column exchange follow the methods of Jorgensen (1977), Klump and Martens (1983), and Howes et al. (1995) for nutrients and metabolism. Upon return to the field laboratory (private residence located near shore of Waquoit Bay), the cores were transferred to pre-equilibrated temperature baths. The headspace water overlying the sediment was replaced, magnetic stirrers emplaced, and the headspace enclosed. Periodic 60 ml water samples were withdrawn (volume replaced with filtered water), filtered into acid leached polyethylene bottles and held on ice for nutrient analysis. Ammonium (Scheiner, 1976) assay was conducted within 24 hours and the remaining sample frozen (-20oC) for assay of nitrate + nitrite (Cd reduction:


2016 Benthic Nutrient Flux Locations

2001 Benthic Nutrient Flux Locations

Figure 13. Sediment nutrient flux locations to determine basin-wide uptake or release. 2016 (left panel) and 2001 (right panel).

Lachat Autoanalysis), and DON (D'Elia et al., 1977). Rates were determined from linear regression of analyte concentrations through time. Chemical analyses were performed by the Coastal Systems Analytical Facility at the School for Marine Science and Technology (SMAST) at the University of Massachusetts in New Bedford, MA. The laboratory follows standard methods for saltwater analysis and sediment geochemistry and has passed review by DEP/USEPA for chemical analysis. All chemical analyses for the 2016 benthic flux effort were consistent with those used for MEP.

Water column nitrogen levels are the balance of inputs from direct sources (land, rain etc), losses (denitrification, burial), regeneration (water column and benthic), and uptake (e.g. photosynthesis). During the warmer summer months the sediments of shallow embayments like the Quashnet / Moonakis River system typically act as a net source of nitrogen to the overlying waters and help to stimulate eutrophication in organic rich systems. However, some sediments may be net sinks for nitrogen and some may be in “balance” (organic N particle settling = nitrogen release). Sediments may also take up dissolved nitrate directly from the water column and convert it to dinitrogen gas (termed “denitrification”), hence effectively removing it from the ecosystem. This process is typically a small component of sediment denitrification in embayment sediments, since the water column nitrogen pool is typically dominated by organic forms of nitrogen, with very low nitrate concentrations. However, this process can be very effective in removing nitrogen loads in some systems, particularly in salt marshes, where overlying waters support high nitrate levels.

Generally, coastal sediments are not overlain by nitrate rich waters and the major nitrogen input is via phytoplankton grazing or direct settling. In these systems, on an annual basis, the amount of nitrogen input to sediments is generally higher than the amount of nitrogen release. This net sink results from the burial of reworked refractory organic compounds, sorption of inorganic nitrogen and generally a relatively large loss through denitrification of produced inorganic nitrogen before it can “escape” to the overlying waters. However, this net sink evaluation of coastal sediments is based upon annual fluxes. If seasonality is taken into account, it is clear that sediments undergo periods of net input and net output. The net output is generally during warmer periods and the net input is during colder periods. The result can be an accumulation of nitrogen within late fall, winter, and early spring and a net release during summer.

Unfortunately, the tendency for net release of nitrogen during warmer periods, coincides with the periods of lowest nutrient related water quality within temperate embayments. This sediment nitrogen release is in part responsible for poor summer nutrient related health. Other major factors causing the seasonal water quality decline are the lower solubility of oxygen during summer, the higher oxygen demand by marine communities, and environmental conditions supportive of high phytoplankton growth rates.

In order to determine the net nitrogen flux between water column and sediments, all of the above factors were taken into account. The net input or release of nitrogen within a specific portion of the embayment in 2016 was determined based upon the measured ammonium release, measured nitrate uptake or release, and estimate of particulate nitrogen input. This was also undertaken for the 2001 benthic nutrient flux assessment used in the MEP assessment (Table 6).

As a point of comparison to the 2016 benthic flux assessment, nitrogen release or uptake from the sediments within the Quashnet / Moonakis River system were determined by the MEP in 2001 and are presented in Table 6. It is clear that the sediments within the more nitrogen loaded regions show the highest nitrogen sources to the overlying waters. Within the Quashnet / Moonakis system, the uppermost portion had the highest nitrogen release. In 2001, the

Quashnet / Moonakis River estuary received more than 2 times the nitrogen loading (on a system area basis) than the other tributary estuaries to Waquoit Bay and had significant organic matter accumulations due to phytoplankton and macroalgal production. In addition, the lower basin (Quashnet Lower) had a “sill” formed by the flood tidal delta which enhanced deposition which is reflected in the nitrogen release rate. The observed sediment release rates within the system was similar in 2001 to the rates and distribution measured by MEP within adjacent Popponesset Bay. Most notably was the similarity between the estuarine reaches of the Quashnet River (mean=67 mg N m^{-2} d^{-1}) and Mashpee River (mean=72 mg N m^{-2} d^{-1}) with their generally similar hydrologic and physical characteristics.

Net nitrogen release rates from Quashnet Estuary sediments was comparable between 2001 and 2016 (Table 6). It must be noted that sediment nitrogen dynamics was measured at the same temperature (22°C) in both years, as temperature can have a significant effect on observed rates.

Table 6. Rates of net nitrogen return from sediments to the overlying waters of the Quashnet River as developed by the MEP (2001) and the present study (2016). These values are combined with the basin areas to determine total nitrogen mass in specific portions of the system. Measurements represent July/August rates. % Denitrified is based upon the measured denitrification rate and the total nitrogen cycled. Sites are pooled by geomorphologic basins. “Q” represents MEP sites.

	Net Flux (mg N m^{-2} d^{-1})					
	2001		2016			
Basin	**mean**	**S.E.**	**mean**	**S.E.**	**% Recycle N Denitrified**	**Station ID * 2016 & 2001**
Upper	**--**	**--**	**16.6**	**25.4**	**88%**	**11,12**
Mid-Upper	**101.4**	**14.8**	**133.2**	**71.9**	**46%**	**9,10 & Q1**
Mid	**49.9**	**47.0**	**92.8**	**34.1**	**2%**	**6,7,8 & Q2**
Lower	**58.8**	**23.3**	**54.9**	**13.8**	**29%**	**1 - 5 & Q3+4**

* Station ID's refer to Figure 13.

Assessment of Habitat Suitability for Shellfish Propagation

An initial step in determining habitat suitability was refer to the Massachusetts Division of Marine Fisheries shellfish suitability maps as well as MassDMF shellfish growing area maps. These maps (Figure 14) were referenced to gauge potential versus actual shellfish utilization. The complete Quashnet / Moonakis River system is presently prohibited to shellfishing and only a small area of the system proximal to the inlet was deemed suitable for shellfish, quahogs and soft shell clams. Historic infaunal data collected under the MEP at three different stations (upper, mid, lower) confirmed the lack of naturally occurring shellfish populations with only 1 benthic species being documented at each of the three stations, and no bivalves. While these data indicate the lack of a natural set of shellfish, they are of limited use for assessing the survival and growth of shellfish such as oysters in managed deployments aimed at mitigating nitrogen overloading. To assess the potential success of large scale deployments, we used smaller experimental deployments of oysters in surface bags and bottom racks to determine where shellfish can be deployed, where oxygen and food conditions maybe favorable and potential predation is controlled. Three (3) sites were assessed for potential future propagation areas, one site in the upper, mid and lower reaches.

Environmental Requirements: *Crassostrea virginica* (Eastern oyster or American oyster) occurs over a wide geographic range being found in estuarine waters from the Gulf of Mexico to the Gulf of St. Lawrence. *C. virginica's* success is attributable to its physiological adaptations, which allow it to survive over a wide range of environmental conditions, e.g. salinity, temperature, dissolved oxygen, food concentration (Kennedy et al. 1996). Unlike other bivalve species e.g. scallops, soft shelled clams, the American Oyster can tightly close its valves and enter a hypometabolic state, thus protecting itself from inhospitable conditions (Rybovich et al. 2016). Though the oyster can survive for weeks in this state, it is neither feeding nor growing.

Salinity and temperature are the master variables controlling oyster physiological functioning (Rybovich et al., 2016). *C. virginica* can tolerate a salinity range of 5 to 30 ppt, but are most successful in saline waters ranging from 10 to 28 PPT (Loosanoff, 1953). Adult oysters inhabiting waters outside of the 5 to 30 ppt range will stop feeding and reproducing. Salinities greater than 7.5 ppt are required for spawning. Oyster growth slows significantly at 7 PPT and ceases at 5 ppt. However, an oyster's ability to tolerate low salinities decreases with increasing temperature (Loosanoff, 1953). Oyster mortality rates are greater in warm low salinity waters than cold low salinity waters. The low salinity waters generally lead to sub-optimal filtration and growth rates. However, oyster drills and predatory starfish are restricted to higher salinity waters (>20 ppt) so increased survival can occur. Decreased mortality attributable to a lack of predators can be a desirable trade-off for bottom raised oysters at the lower range of acceptable salinities.

The ability to close their valve tightly allows oysters to survive hypoxic (low oxygen) and anoxic (no oxygen) conditions for short periods. Oyster filtering activity will slow and cease once dissolved oxygen concentrations decrease below 2 mg/l (Cerco and Noel, 2005). Oysters tolerate anoxic conditions by reducing their metabolic rates (Stickle et al. 1989). *C. virginica* tolerance of anoxic conditions decreases with increasing temperature as it demands increased respiration rates (Stickle et al. 1989). Lastly, oyster filtration is greatest when particulate concentrations (TSS) are between 5 and 10 mg/L (Newell and Langdon, 1996).

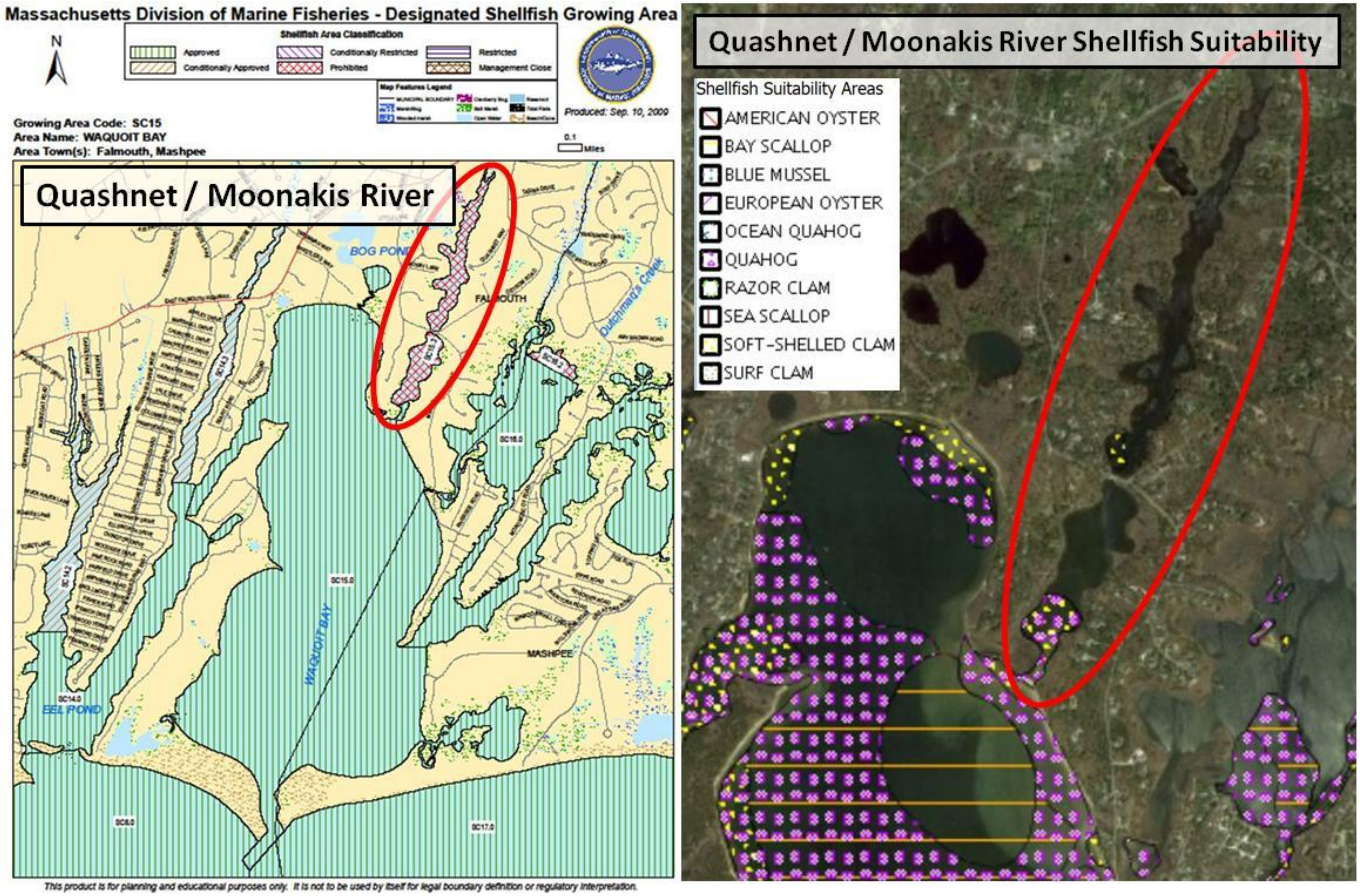


Figure 14. Massachusetts Division of Marine Fisheries (MassDMF) Map of the status of harvest in shellfish growing areas (left). The Quashnet Estuary is presently prohibited for shellfish harvest requiring relay prior to consumption. MassDMF map of Shellfish Suitability for the Quashnet River / Moonakis River system tributary to Waquoit Bay (right). Suitability does not mean those shellfish are currently present.

Quashnet River Oyster Deployment 2016: Oyster survival and growth rate was examined in the upper and lower regions of the Quashnet Estuary in 2016. To this end oysters were deployed in floating surface bags and bottom trays to evaluate the potential for future large deployments for the purpose of intercepting nitrogen prior to discharge to Waquoit Bay as a non-traditional nitrogen management alternative and to examine the potential for aquaculture in general in this phytoplankton rich system.

Examining available data prior to this study, it appeared that within the Quashnet Estuary the conditions for oyster growth and survival generally existed. The high particulate and phytoplankton levels throughout most of its tidal reach should support rapid growth and there appeared to be few invertebrate predators. However, there was a concern that low salinities in the upper reaches might inhibit growth to the extent that they were encountered. To this end particulate and chlorophyll-*a* levels and salinity was monitored at each deployment site.

Single set oyster seed (22 mm) was deployed at three stations in the Quashnet River on 7/26/2016 (Figure 15). Two surface bags and one bottom tray were deployed at each station. Oysters (300 individuals) were deployed in surface floating bags (0.5 m^2 diamond mesh bags) and 1 m^2 bottom trays (covered and with plastic mesh liner to reduce predation).

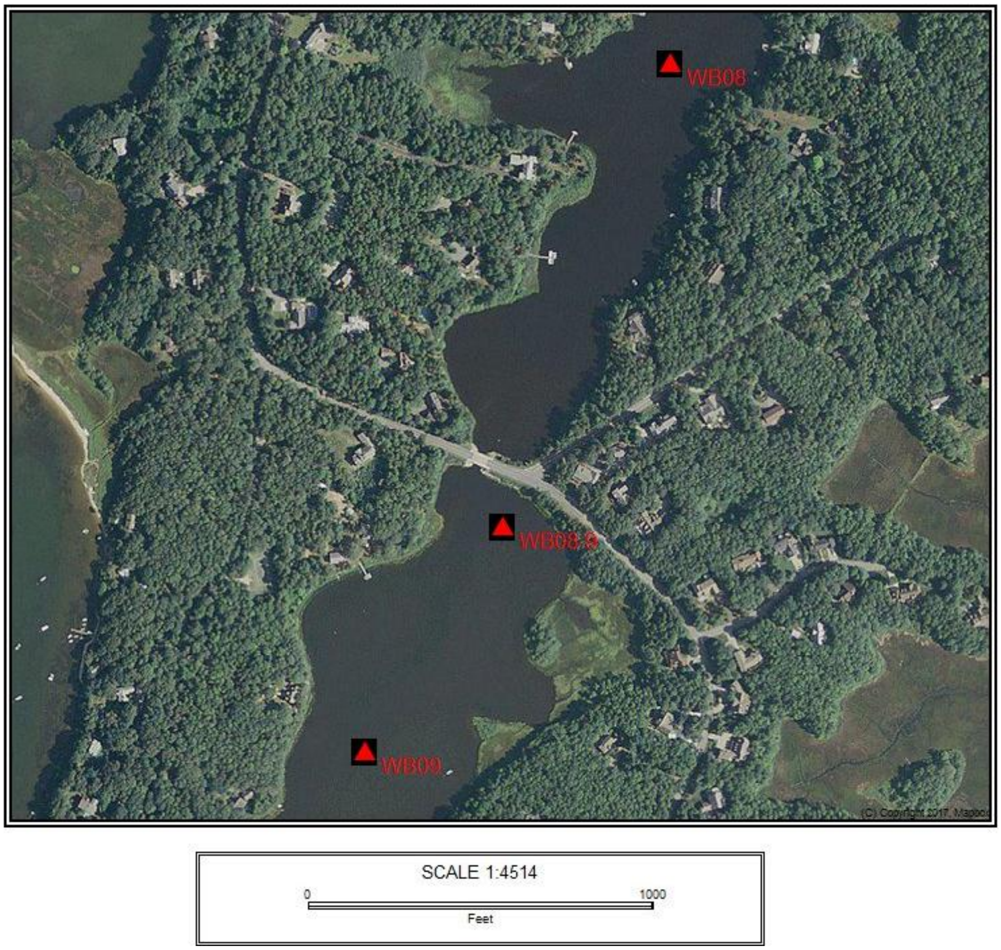


Figure 15. Map of the Quashnet Estuary showing the three oyster deployment stations in 2016. GPS coordinates: WB08: N 41.58167, W 70.51248; WB08-9: N 41.57798, W 70.51427; WB09: N 41.57618, W 70.51573

Oyster Mortality and Growth: Oyster mortality was greatest in the WB08 surface bags (Table 7) where salinities were generally <3 ppt, lower than the 5 ppt acceptable salinity for oyster habitat. In addition, growth in surviving oysters was negligible. The low salinity for the surface bags resulted from estuarine circulation with freshwater entering from the river flowing out over the more saline waters below (Figure 16).

Table 7. Cumulative oyster mortality and seasonal growth rates. Surface bag mortalities were averaged for each station. Monthly growth rates were based on shell height (umbo to bill). Site ID's refer to Figure 15.

Station ID		**Salinity (ppt)**	**Monthly Growth (mm/month)**			**Mortality**
		Average	**Summer**	**Fall**	**Total**	**Cummulative**
WB08 Upper Basin	**Surface Bags**	1.5	0	0	0	48.7%
	Bottom Tray	10.4	13.73	5.83	9.20	1.2%
WB08-9 Mid	**Surface Bags**	---	16.48	4.14	9.20	0.2%
	Bottom Tray	---	12.35	3.55	7.31	1.4%
WB09 Lower Basin	**Surface Bags**	20.6	17.26	3.48	9.28	0.1%
	Bottom Tray	22.0	11.66	3.46	6.97	3.7%

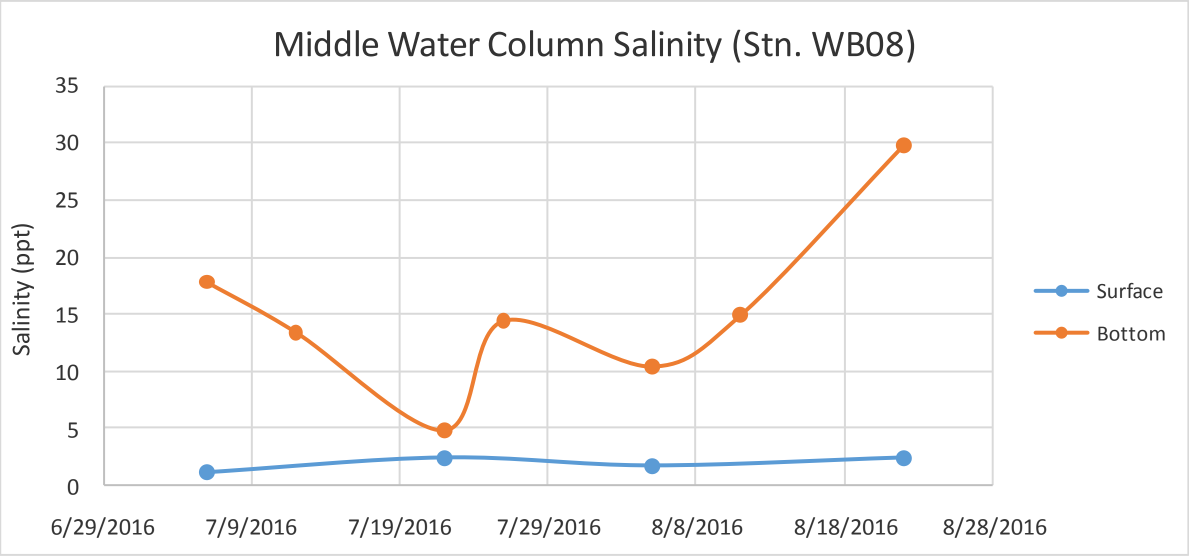


Figure 16. WB08 salinity of surface and bottom water collected during mid-ebb tide Surface salinities collected on a mid-ebb tide were less than 3 PPT during the months of July and August.

Oyster growth rates are highest during its first few months of life (Bahr, 1976). Phytoplankton density, size, and species composition strongly influence oyster growth rates (Stanley and Sellers, 1986).

Oysters can effectively capture and consume particles larger than 3 μm in diameter (Jorgensen and Goldberg, 1953). The pore size of filters used to determine particulate organic carbon and Chlorophyll-*a* are 0.45 and 0.22 um, respectively, which slightly overestimates the available food supply, although almost all phytoplankton are >3 μm. While there was relatively high particulate organic carbon in the water column at the deployment sites over the summer (Figure 17), determination of particulate organic carbon (POC) does not discern between labile and refractory forms, the latter being a less energetically valuable food source (Soniat et al., 1984). However, the high chlorophyll-*a* levels suggest that most of the POC was in the form of phytoplankton (Figure 18). This is consistent with monthly growth rates (Table 8) being comparable or greater than growth rates reported for aquaculture oysters grown in NY, CT, and NJ embayments (Kraeuter et al., 2007). Consequently, it is reasonable to assume that the available seston consisted of labile organic matter (phytoplankton) within an accessible size range and at densities supportive of oyster growth.

Oyster growth was greatest in salinities >10 ppt during the summer when food availability was greatest and temperatures warmest. Oysters grown in surface bags (with the exception of WB08, which exhibited no growth at <3ppt) had higher growth rates than oysters grown in bottom trays. This result is not surprising as published research has found higher growth rates in suspended oysters compared to bottom reared oysters attributable to warmer surface waters and higher food concentrations (Bataller et al., 1999; Comeau et al. 2010).

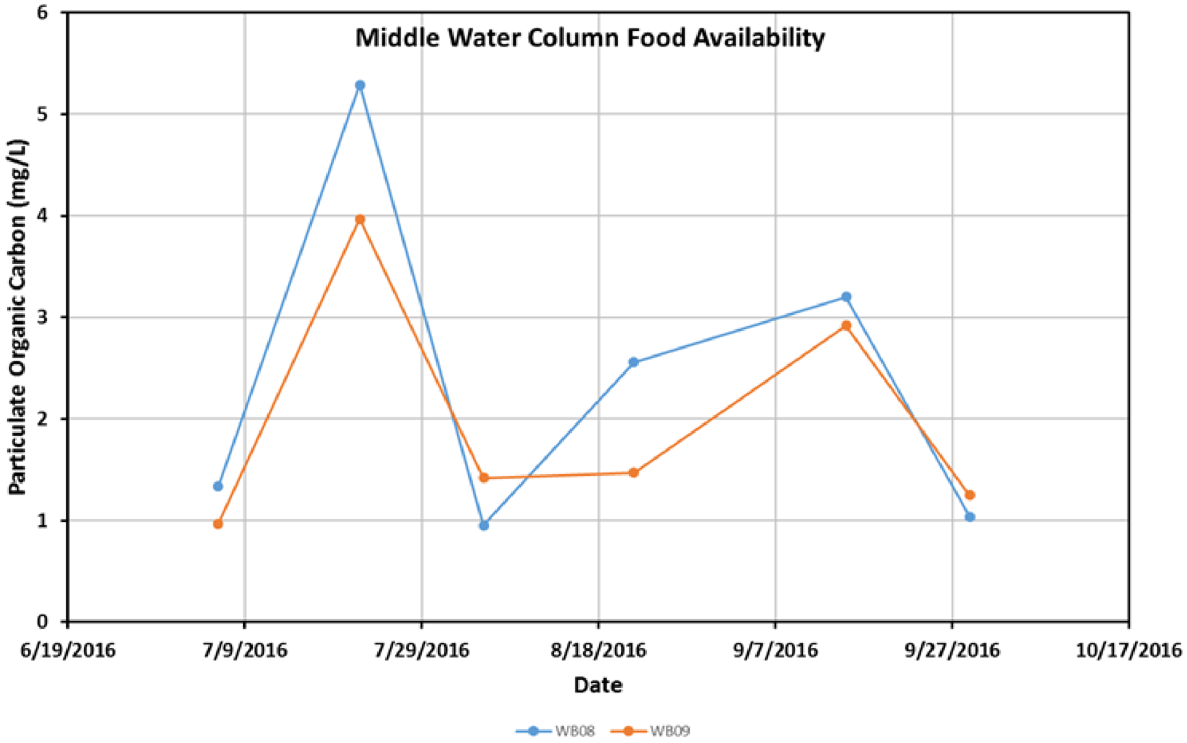


Figure 17. Water column particulate organic carbon concentration (mg C/l) determined from water quality samples collected mid-depth during summer and fall of 2016 at WB08 (blue) and WB09 (red). Station number refer to deployment sites in Figure 15.

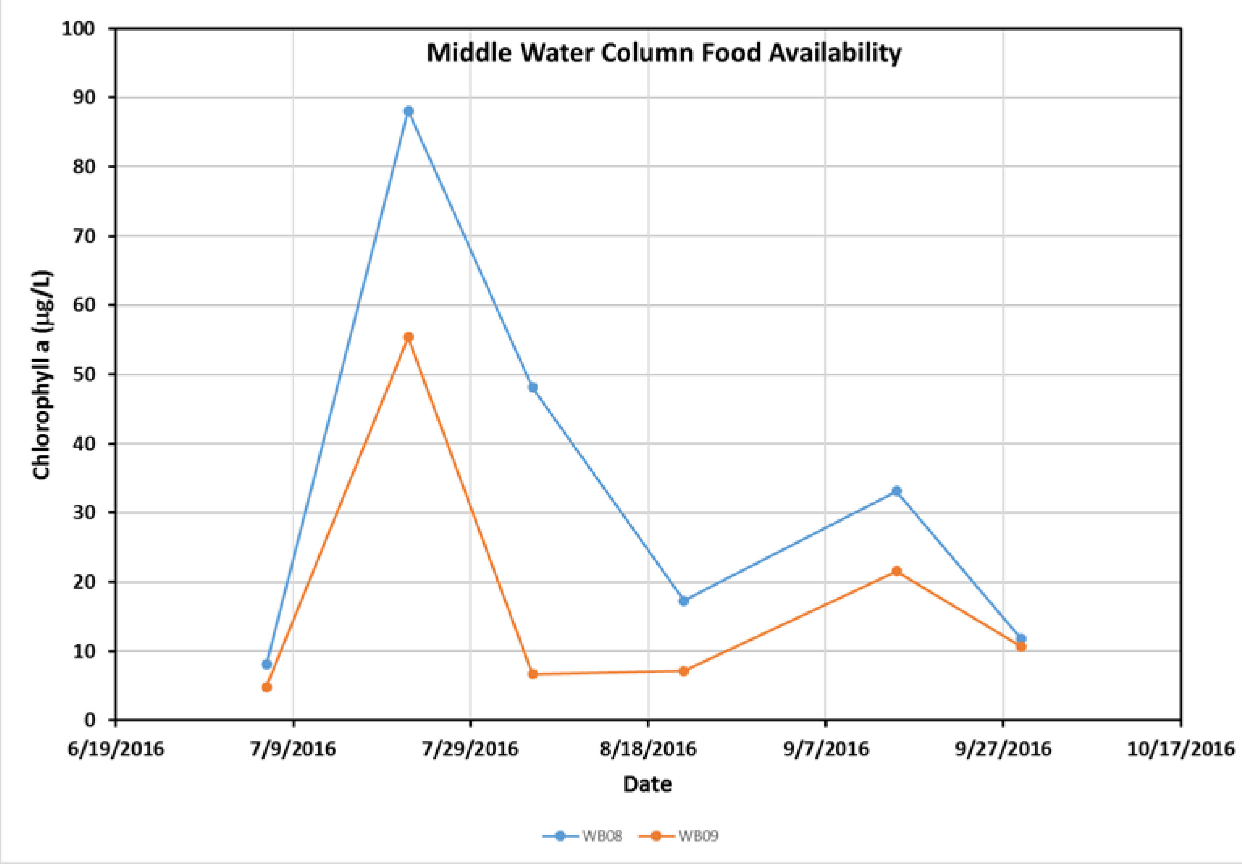


Figure 18. Water column Chlorophyll-a concentration (ug/l) determined from water quality samples collected mid-depth during summer and fall of 2016 at WB08 (blue) and WB09 (red). Station number refer to deployment sites in Figure 15.

Disease, predation, and fouling: Bags and bottom racks at WB09 and WB08-9 had extensive macroalgal growth while WB08 had no macroalgal growth (Figure 19 left and 19 right, respectively). Macroalgal fouling of the WB09 bottom tray likely reduced food available to the oysters by impeding flow and the flux of particulates through the tray (Leavitt, 2017). The lack of macroalgal growth on the WB08 bottom tray compared to the WB09 and WB08-9 bottom trays could explain the increased oyster shell growth observed in the WB08 bottom tray (Table 8). The difference in shell growth rates is especially clear in the fall when the accumulation of fouling organisms was greatest. The lower bottom salinity (maximum= ~27 ppt, minimum = ~1 ppt) and periodic short term hypoxia at WB08 likely prevented macroalgal fouling of the bottom tray. Salinities between 5ppt and 12 ppt are recommended to reduce incidences of disease and predation (Kennedy et al. 1996). However, oyster filtration rates, and thus growth rates, increase with increasing salinity (Enrich and Harris, 2012). Apparently the occasional reduction in feeding during hypoxia had a lower impact on growth than the higher flow through the racks from low fouling. Common oyster predators include the oyster drills, whelks, crabs, Oyster Toadfish, Oyster Flatworms, and Cownose Rays (Leavitt, 2017). Small crabs were observed in the WB08-9 and WB09 bottom trays; however, mortality rates were close to zero (Table 7) and no mortality could be ascribed to predation. The physical barrier created by the bottom tray and mesh liner provided sufficient protection to maintain low predation rates.

Figure 19. (Left) WB08 bottom cage on 8/29/16, (right) WB09 bottom cage on 8/29/16.

Dissolved Oxygen and Chlorophyll (MEP 2002 + 2016)

A record of oxygen conditions is critical as part of the feasibility determination for shellfish propagation. Experience by the Town of Falmouth in Little Pond found that early season hypoxia caused death to the spat as well as to small oysters initially grown out in surface bags. Hypoxic surface waters were not anticipated in that effort, but recent changes in tidal exchange supported high rates of oxygen consumption and stratification resulting in hypoxia and unanticipated shellfish loss, which required extra effort to address. The current effort, completed in the summer of 2016, focused on collecting new DO data at three (3) locations (Figure 20) along the length of the system to ascertain the likelihood of hypoxia occurring at each site while also characterizing light levels, potential stratification, salinity and oxygen uptake. The results form the basis for developing a warning protocol for future propagation activities in this system.

As part of the habitat suitability assessment for oysters, phytoplankton biomass (chlorophyll-a) was monitored based on periodic grab samples and time-series sensor measurements (YSI 6600 recording at 15 minute intervals) from May through October (main growing season). This was conducted in each of the 3 major estuarine reaches at the same locations with experimental grow-out bags containing both small and large shellfish. Oysters were selected as a preferred species as the brackish waters of the upper basins of the Quashnet River are ideal for oysters and they can be grown in bags and bottom cages as most appropriate given environmental conditions. Additionally, the low salinity water found in the uppermost basin (the most eutrophic of the system) should reduce predation. Placing oysters in brackish low salinity water has been used in propagation historically, as a key predator, the oyster drill (Urosalpinx) are generally not present. To gauge the level of predation, small oysters were placed in floating bags to gauge predation and mortality. From the array of measures, it was possible to get an initial survey of the areas within the Quashnet estuary supportive of the highest rates of growth, lowest rates of loss through hypoxia and lowest rates of predation.

Similar to other embayments across southeastern Massachusetts, the Quashnet River / Moonakis River system has historically shown high frequency variation in dissolved oxygen, apparently related to diurnal and sometimes tidal influences. The high degree of temporal variation in bottom water dissolved oxygen concentration underscores the need for continuous monitoring through mooring deployments to accurately characterize DO and chlorophyll conditions in the system. This was undertaken both through the MEP in 2002 (Figure 21) and was repeated at a higher spatial resolution in 2016 (Figure 20). It is important to note that from a habitat quality point of view, nitrogen enrichment of embayment waters generally manifests itself in the dissolved oxygen record, both through oxygen depletion and through the magnitude of the daily oxygen excursions.

Based on the oxygen data collected by the MEP in 2002 for the tidally influenced lower Quashnet River (Figure 22), this lower portion of the system between the inlet to Waquoit Bay and Meadow Neck Road bridge clearly showed a high level of oxygen stress. In the 2002 Quashnet River record, dissolved oxygen levels frequently dropped to less than 4 mg L-1 during the night and reached levels in excess of atmospheric saturation during the day time (Figure 22).

Figure 20. 2016 Dissolved Oxygen / Chlorophyll Mooring deployment locations in the Quashnet River / Moonakis River.

The 2002 dissolved oxygen records were further analyzed to determine the percent of the deployment time (29-37 days) that oxygen was below various benchmark concentrations (Table 8a). These data indicate not just the minimum or maximum levels of dissolved oxygen, but the frequency and duration of the low oxygen circumstances. From the 2002 oxygen record the Quashnet River had the greatest extent of oxygen depletion of all the moorings deployed for the MEP Waquoit Bay nutrient threshold analysis and the oxygen excursion indicated a high degree of nutrient enrichment (also supported by the chlorophyll-*a* data, Figure 23). It is important to note that in 2002, the DO data were only from the lower part of the system, which would tend to have the highest water quality. Even so, the oxygen levels in 2002 were <4 mg L^{-1} 8% of the time. In 2002, the Quashnet River data indicated that daily excursions of 15 mg L^{-1} in bottom water oxygen did occur. Another clear sign of habitat impairment in the Quashnet River.

Historic chlorophyll-*a* data for the Quashnet River sub-embayment to Waquoit Bay was of sufficient size to allow a frequency analysis similar to that completed for dissolved oxygen (Table 8c). The historic Mashpee/SMAST data (stations WB-07,08,09, Figure 24) were mainly used for the 2002 MEP analysis, however, historic Baywatch data collected by the Buzzards Bay Coalition are provided for comparison, as it is a longer dataset. Both data sets show similar patterns of nitrogen related impaired habitat quality. From the historic data it is clear that in 2002 the Quashnet River was a highly eutrophic system with total chlorophyll-*a* levels in the upper and mid regions averaging >20 μg L^{-1} (SMAST data presented in Figure 22, 23). The moored chlorophyll sensor showed similarly high values (Table 8b). Based on the 2002 chlorophyll record, phytoplankton blooms appear to be generated within the upper and mid basins of the Quashnet, most likely as a result of the high nitrogen loading to the headwaters via the Quashnet River freshwater discharge. On three historic sampling events the Quashnet upper station showed exceedingly large blooms (>140 μg L^{-1}), while on three separate events the mid station showed very large blooms (>40 μg L^{-1}).

Based on the 2002 DO and CHLA data, the Quashnet River did not clearly show the typical relationship of high phytoplankton biomass to high oxygen stress, however, this may be in part due to the 2002 placement of the oxygen mooring in the lower basin which would have supported lower phytoplankton than the mid and upper stations above the Meadow Neck road bridge. Anecdotal evidence of large quantities of macroalgae provide another possible explanation. Historic traditional “grab” sampling data were available for the mid station. These data indicated a high degree of oxygen depletion with almost one third of the sampling dates showing oxygen levels <4 mg L^{-1}. This pattern is also seen in the limited historic oxygen data from the upper region of this system. Taken in whole, it appears that in 2002 and before, the Quashnet River Estuary was showing oxygen stress throughout its reach and it is likely that the level of depletion was higher in the upper and mid reaches than in the lower basin, consistent with the historic distribution of phytoplankton biomass.

Combining the dissolved oxygen and chlorophyll-*a* data collected by the MEP in 2002 yielded a clear pattern of nutrient related habitat quality impairment. In 2002, the Quashnet River estuary showed poor oxygen status (based upon depletions, daily excursions, mooring in lower basin) and large phytoplankton blooms (Figure 25). While the system appeared stressed throughout, there was a clear gradient from hypereutrophic in the upper regions to eutrophic in the lower basin. Based upon the 2002 dissolved oxygen and chlorophyll data the nutrient related habitat quality of the Quashnet River estuary was significantly impaired.

While the historical dissolved oxygen and chlorophyll data utilized in the MEP analysis clearly demonstrate habitat impairment in the Quashnet River, the spatial extent of the data collected was more focused on the lower section between the inlet and the Meadow Neck Road bridge crossing. As such, for the current habitat suitability assessment, the CSP science team deployed a series of moorings in the upper, middle and lower sections of the Quashnet / Moonakis River system to get an updated measure of DO and CHLA conditions (plus salinity and temperature) along the length of the sub-estuary. Three moorings were deployed (July 2016) and collected measurements for a total of (~111) days.

Figure 21. Aerial Photograph of the Waquoit Bay Embayment System within the Towns of Falmouth and Mashpee showing locations of Dissolved Oxygen mooring deployments conducted by the MEP in summer 2002 (Quashnet River and Hamblin Pond) and in the summer of 2007 (main basin Waquoit Bay, Childs River and Eel Pond). Yellow symbols show instrument locations. Green symbols are WBNERR deployed long term DO mooring stations.

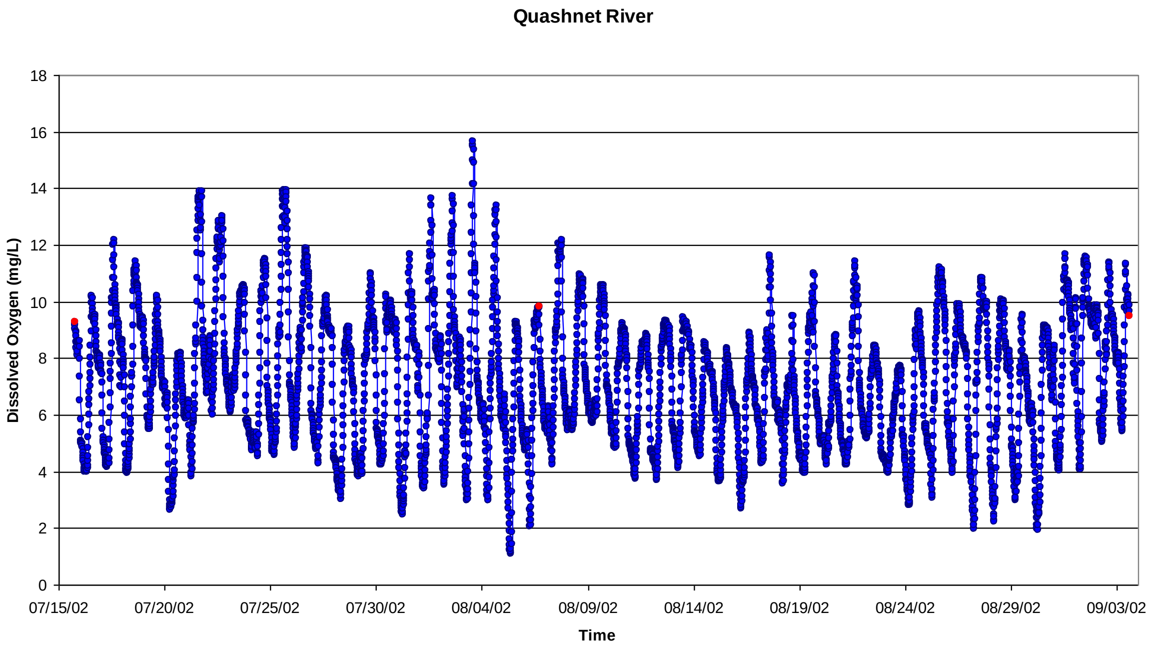


Figure 22. Bottom water record of dissolved oxygen (top panel) in the Quashnet River Estuary (lower basin), summer 2002. Calibration samples represented as red dots.

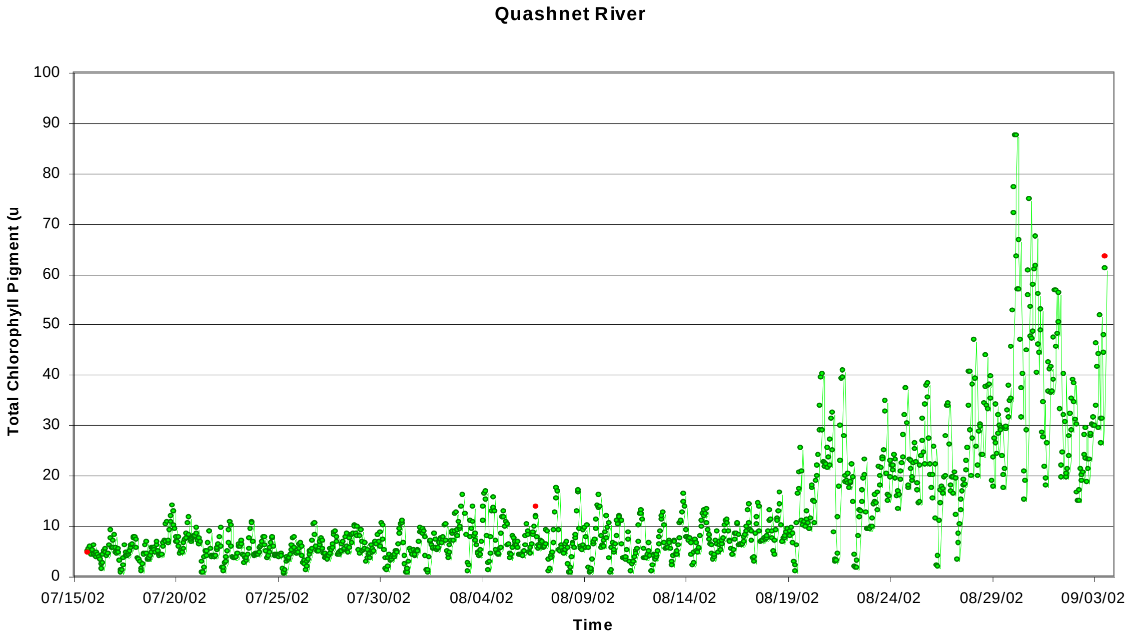
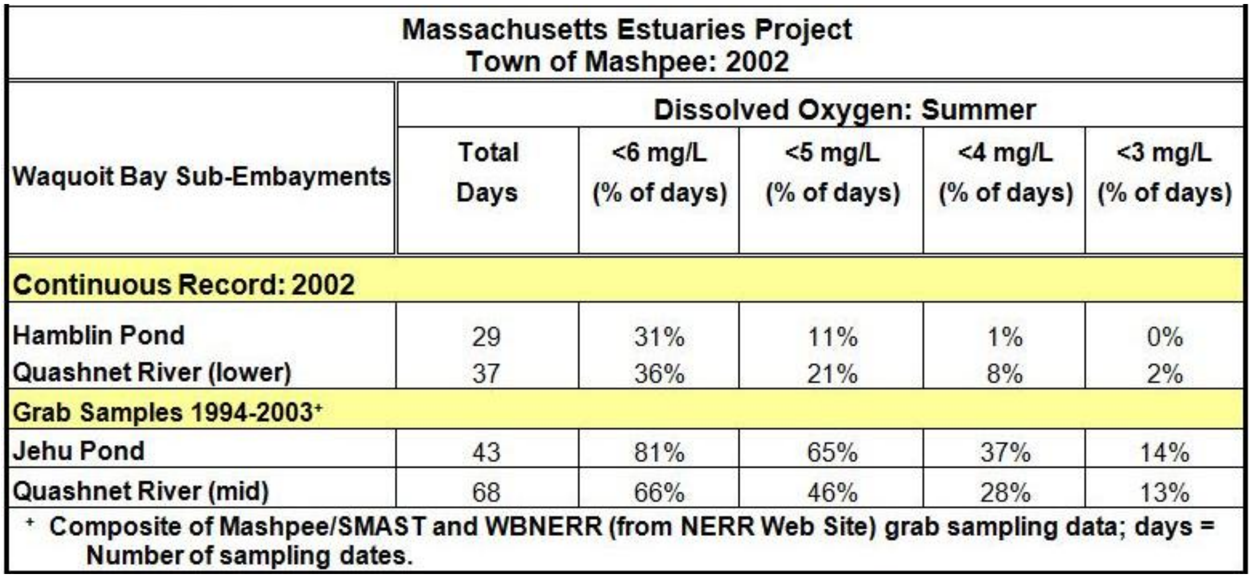


Figure 23. Bottom water record of chlorophyll-*a* (bottom panel) in the Quashnet River Estuary (lower basin), summer 2002. Calibration samples represented as red dots

Table 8a. Frequency (number of events during deployment) and duration (total number of days over deployment) of dissolved oxygen levels below various benchmark levels from MEP continuous records from Quashnet River (2002).

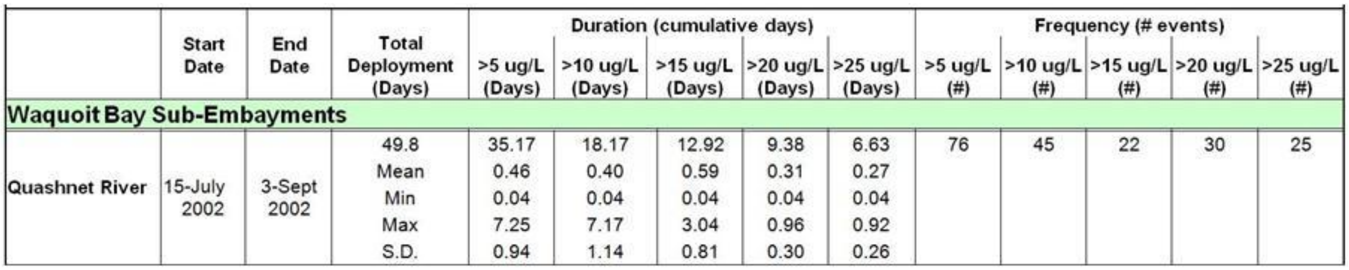


Massachusetts Estuaries Project
Town of Mashpee: 2002

Waquoit Bay Sub-Embayments	Dissolved Oxygen: Summer				
	Total Days	<6 mg/L (% of days)	<5 mg/L (% of days)	<4 mg/L (% of days)	<3 mg/L (% of days)
Continuous Record: 2002					
Hamblin Pond	29	31%	11%	1%	0%
Quashnet River (lower)	37	36%	21%	8%	2%
Grab Samples 1994-2003⁺					
Jehu Pond	43	81%	65%	37%	14%
Quashnet River (mid)	68	66%	46%	28%	13%

⁺ Composite of Mashpee/SMAST and WBNERR (from NERR Web Site) grab sampling data; days = Number of sampling dates.

Table 8b. Frequency (number of events during deployment) and duration (total number of days over deployment) of chlorophyll a levels above various benchmark levels from MEP continuous records from Quashnet River (2002).



	Start Date	End Date	Total Deployment (Days)	Duration (cumulative days)					Frequency (# events)				
				>5 ug/L (Days)	>10 ug/L (Days)	>15 ug/L (Days)	>20 ug/L (Days)	>25 ug/L (Days)	>5 ug/L (#)	>10 ug/L (#)	>15 ug/L (#)	>20 ug/L (#)	>25 ug/L (#)
Waquoit Bay Sub-Embayments													
Quashnet River	15-July 2002	3-Sept 2002	49.8	35.17	18.17	12.92	9.38	6.63	76	45	22	30	25
			Mean	0.46	0.40	0.59	0.31	0.27					
			Min	0.04	0.04	0.04	0.04	0.04					
			Max	7.25	7.17	3.04	0.96	0.92					
			S.D.	0.94	1.14	0.81	0.30	0.26					

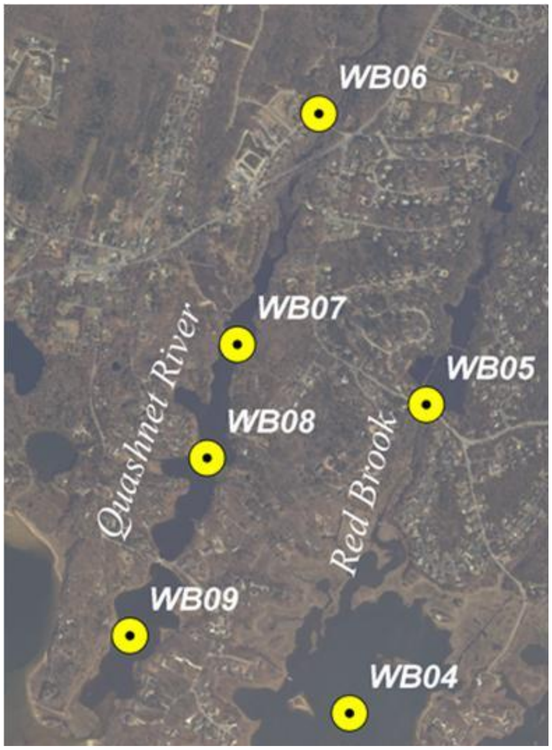


Figure 24. Location of Quashnet River water quality sampling stations that are part of the broader Waquoit Bay sampling station network. Station WB09 is in the same location as the Quashnet River mooring location from the MEP as well as the Quashnet Lower mooring location from the current study.

Table 8c. Chlorophyll-a data obtained from the Quashnet River water quality monitoring stations from 2001-2003. These data are from the collection of discrete grab samples during the summer from 2001 to 2003 (June-Sept.) as opposed to values obtained from a moored instrument. Levels of chlorophyll a pigments within the Town of Mashpee Quashnet / Moonakis River sub-embayment to Waquoit Bay. Data collected by the Waquoit Bay BayWatcher Program (WBNERR) and by Popponesset Bay Water Quality Monitoring Program and Coastal Systems Program, SMAST (SMAST). Geometric averages were used to estimate "average" conditions, given the periodic phytoplankton blooms. WBNERR data (June-September) is from the BayWatcher samplings garnered from NERR Web site.

	Sampling			Statistics				
	Source	Station	Year	Geo Mean ug/L	Geo Stdev ug/L	Max ug/L	Min ug/L	N
Waquoit Bay Sub-Embayments								
Quashnet River								
Upper	WBNERR	--	–	–	–	--	--	–
Upper	SMAST	WB-07	2001-2003	22.7	4.1	168.8	2.7	11
Mid	WBNERR	Site 5	1998-2002	4.6	3.6	80.2	0.6	34
Mid	SMAST	WB-08	2001-2003	20.1	2.1	53.2	5.5	11
Lower	WBNERR	--	–	–	–	--	--	–
Lower	SMAST	WB-09	2001-2003	9.7	2.0	44.5	4.8	12

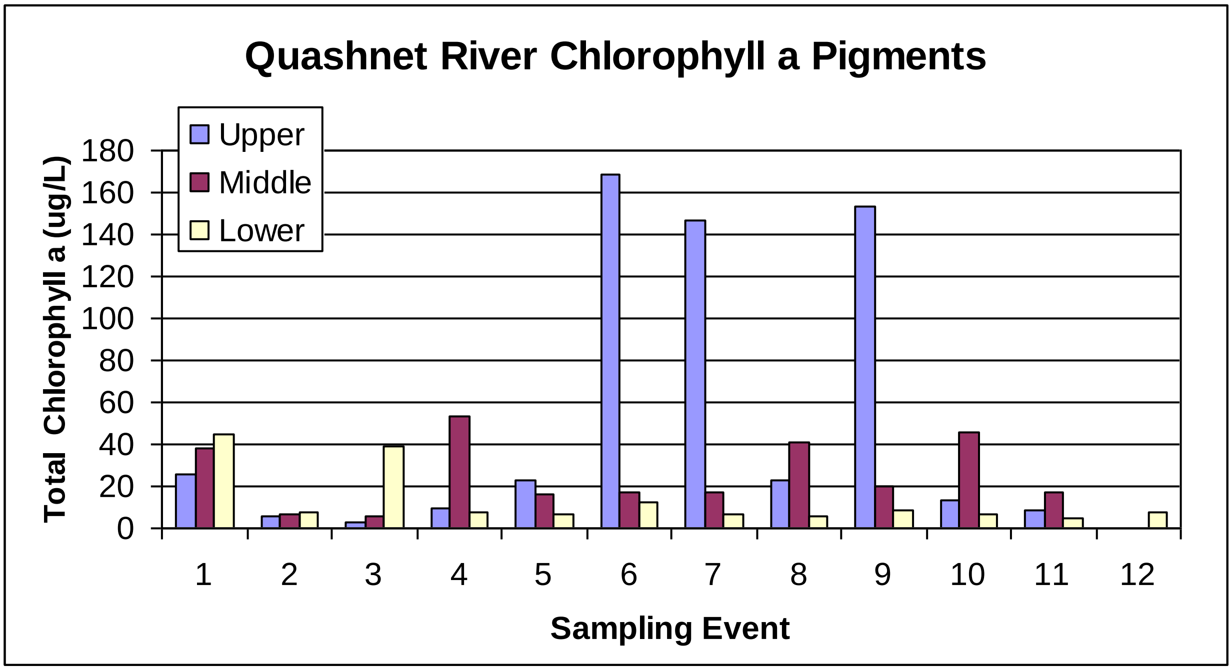


Figure 25. Distribution of chlorophyll a pigments in the Quashnet River Estuary from grab sampling; Mashpee Water Quality Monitoring Program-Coastal Systems Program (SMAST) 2001 - 2003.

As part of the current assessment effort, three YSI-6600 dissolved oxygen/chlorophyll moorings were deployed consistent with protocols followed under the MEP for data collection described above. The deployments were completed in the summer of 2016 and focused on collecting new DO and chlorophyll data at three (3) locations (Figure 20) along the length of the system to ascertain the likelihood of hypoxia occurring at each site while also characterizing light levels, potential stratification, salinity and total pigment. The results form the basis for developing a warning protocol for future propagation activities in this system and are biological indicators of habitat suitability for growing a substantive population of oysters in this estuary.

As expected, the upper reach of the Quashnet / Moonakis River system (Quashnet River Upper mooring) showed the largest and consistent variation in salinity and temperature, mainly due to the large input of freshwater entering the head of the system as well as the shallow characteristics of this portion of the system (Figure 26). Salinity ranged from 0 ppt to 20-25 ppt, making it a very stressful environment for oysters and benthic infauna in general. Salinity measured at the Quashnet River Mid mooring location (Figure 27) also showed large variations similar to what was observed at the Quashnet Upper mooring location, however, the record showed periods of time when salinity did not drop below 10 ppt. That was rarely the case at the Quashnet Upper mooring location, thus making the Quashnet Mid location a potentially less stressful portion of the system. The Quashnet Lower mooring showed consistent salinities above 20 ppt (Figure 28).

Dissolved oxygen records from the moorings showed both hypoxia and extreme diurnal variation at all three of the mooring locations (Figures 26, 27 and 28). The duration and frequency of hypoxia (Table 9) were similar to or more impaired than previous instrument deployments (Table 8a). Despite worsening conditions with respect to dissolved oxygen, the impact on oyster growth and mortality were insignificant compared to factors such as salinity which affected surface oyster bags.

Measures of total pigment at both Quashnet River Upper and the Quashnet River Mid mooring locations were relatively similar with average total pigment levels at each location being 46 and 59 ug/L respectively (Figure 26 and 27). Total pigment at both locations exceed the 10 ug/L threshold for impairment 20% and 23% of the total deployment period (111 days) with maximum total pigment concentrations reaching 150 ug/L and 200 ug/L respectively (Table 10). Average chlorophyll-a levels over 10 ug L^{-1} have been used to indicate eutrophic conditions in embayments (Cooksey et. al., 2010). It is important to note that these high total pigment levels may in part be due to the significant macroalgal accumulations observed during the deployment period. Even so, historic CHLA data from grab samples collected in 2001-2003 from the upper Quashnet River (station WB-07) showed maximum concentrations reaching 169 ug/L, consistent with levels observed in 2016.

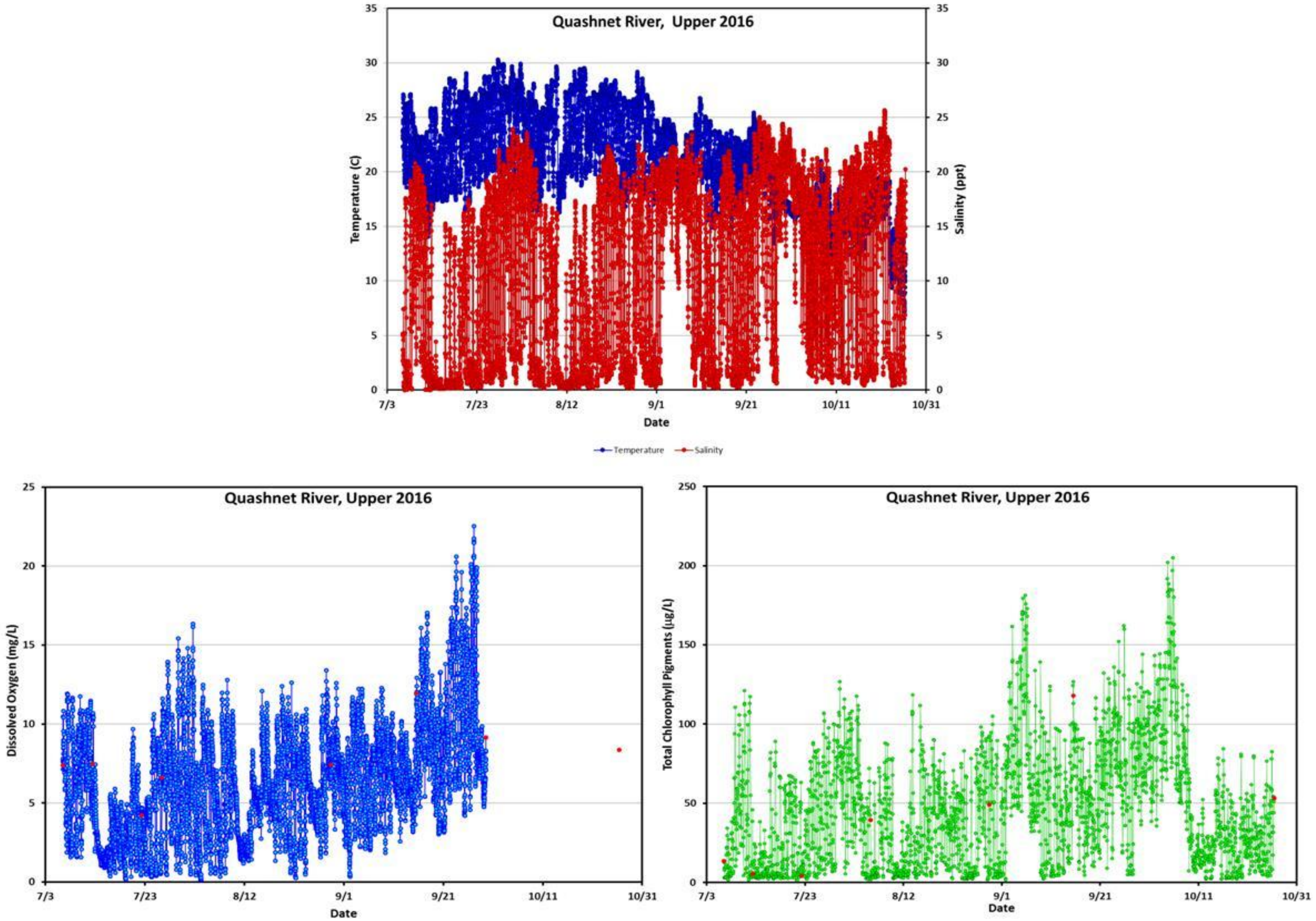


Figure 26. Upper Quashnet Estuary time-series temperature and salinity (top panel), bottom water dissolved oxygen (bottom left panel), and chlorophyll a (bottom right panel) in 2016.

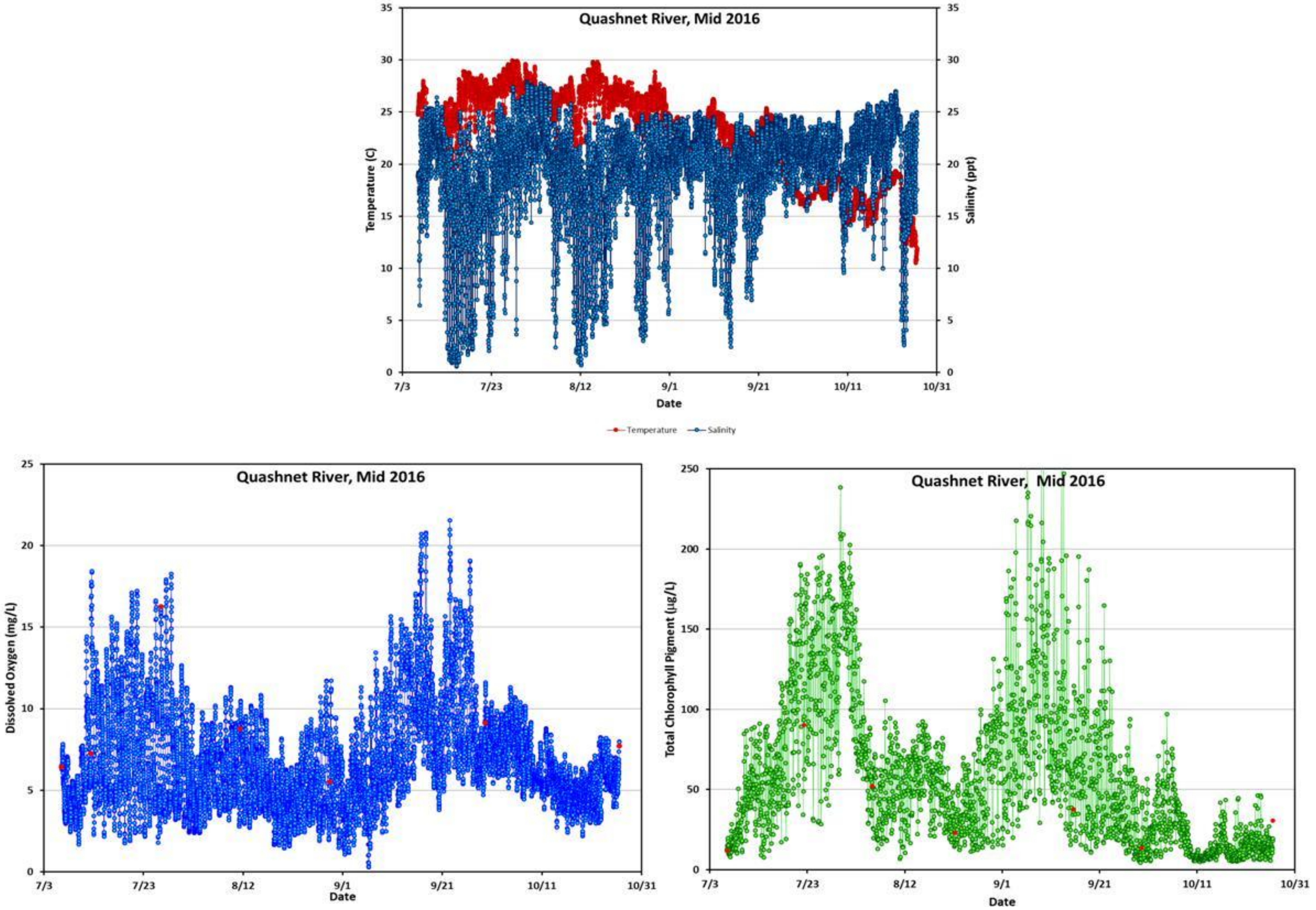


Figure 27. Mid Quashnet Estuary time-series temperature and salinity (top panel), bottom water dissolved oxygen (bottom left panel), and chlorophyll a (bottom right panel) in 2016.

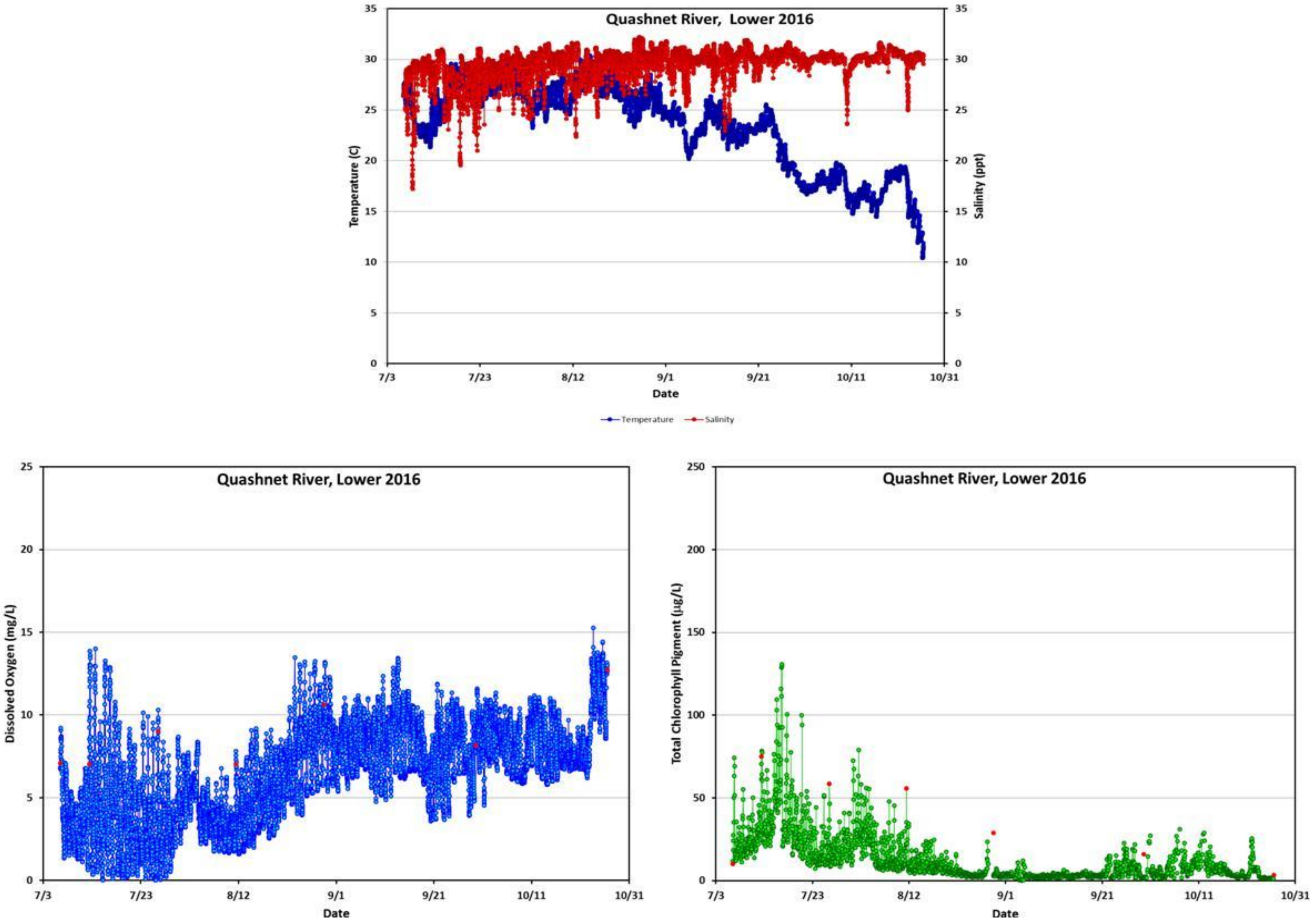


Figure 28. Lower Quashnet Estuary time-series temperature and salinity (top panel), bottom water dissolved oxygen (bottom left panel), and chlorophyll a (bottom right panel) in 2016.

Table 9. Frequency (number of events during deployment) and duration (total number of days over deployment) of dissolved oxygen levels below various benchmark levels from MEP continuous records from Quashnet River (2016).

Deployment Location	Start Date	End Date	Total Deployment (Days)	<6 mg/L Duration (Days)	<5 mg/L Duration (Days)	<4 mg/L Duration (Days)	<3 mg/L Duration (Days)
Quashnet River Upper	7/6/2016	10/26/2016	85.1	45%	36%	26%	18%
			Mean	0.30	0.26	0.20	0.15
			Min	0.01	0.01	0.01	0.01
			Max	7.35	3.00	2.79	2.50
			S.D.	0.82	0.47	0.37	0.29
Quashnet River Mid	7/6/2016	10/26/2016	112.0	35%	25%	16%	5%
			Mean	0.35	0.22	0.13	0.07
			Min	0.01	0.01	0.01	0.01
			Max	2.65	0.76	0.61	0.28
			S.D.	0.35	0.21	0.12	0.07
Quashnet River Lower	7/6/2016	10/26/2016	111.9	39%	29%	21%	12%
			Mean	0.46	0.36	0.25	0.20
			Min	0.01	0.01	0.01	0.01
			Max	3.79	1.85	0.93	0.70
			S.D.	0.57	0.41	0.26	0.18

Table 10. Frequency (number of events during deployment) and duration (total number of days over deployment) of chlorophyll a levels above various benchmark levels from MEP continuous records from Quashnet River (2002).

Deployment Location	Start Date	End Date	Total Deployment (Days)	>5 ug/L Duration (Days)	>10 ug/L Duration (Days)	>15 ug/L Duration (Days)	>20 ug/L Duration (Days)	>25 ug/L Duration (Days)
Quashnet River Upper	7/6/2016	10/26/2016	111.8	22%	20%	18%	17%	16%
Mean Chl Value = 46.4 ug/L			Mean	0.22	0.16	0.13	0.12	0.10
			Min	0.01	0.01	0.01	0.01	0.01
			Max	2.18	1.57	1.57	1.57	1.56
			S.D.	0.39	0.24	0.17	0.16	0.16
Quashnet River Mid	7/6/2016	10/26/2016	111.4	25%	23%	21%	19%	18%
Mean Chl Value = 58.9 ug/L			Mean	1.46	0.36	0.23	0.19	0.14
			Min	0.07	0.01	0.01	0.01	0.01
			Max	8.64	6.73	5.55	4.46	4.46
			S.D.	2.50	1.14	0.71	0.53	0.49
Quashnet River Lower	7/6/2016	10/26/2016	103.6	15%	10%	7%	5%	4%
Mean Chl Value = 12.7 ug/L			Mean	0.09	0.07	0.06	0.05	0.04
			Min	0.01	0.01	0.01	0.01	0.01
			Max	1.77	1.76	0.91	0.91	0.63
			S.D.	0.22	0.20	0.12	0.11	0.07

Management Related Conclusions:

The present study was focused on (1) updating the MEP evaluation of nutrient related health of the Quashnet River Estuary and (2) examining two proposed non-traditional nitrogen management options for managing nitrogen withn this sub-estuary to Waquoit Bay. The 2 nitrogen management options being evaluated were (a) the potential for enhanced tidal exchange both within the Quashnet Estuary (upper and lower basins) and between this sub-estuary and the main basin of Waquoit Bay and (b) the possibility of in-estuary nitrogen management through aquaculture. In the latter option, the focus was to determine the growth and survival of oysters in the lower and mid basins of the Quashnet Estuary. It should be noted that once a plan for nitrogen reduction within this tributary to Waquoit Bay is developed, its impact on the Quashnet Estuary and the entire Waquoit Bay estuary should be assessed using the existing MEP Linked Model for Waquoit Bay.

Specific findings:

- Surveys in 2016 indicate that the Quashnet Estuary remains highly impaired by nitrogen enrichment, with hypoxic bottom waters, macroalgal accumulations and phytoplankton blooms throughout, but reaching >200 ug/L chlorophyll a in the upper basin. This sub-estuary has not improved over the past 10 years and may have declined as the blooms become prolonged and now span the upper and mid basins, as seen in the blooms recorded in 2016. Phytoplankton blooms have been very large over the past nearly 2 decades. The nitrogen levels and large blooms are consistent with the periodic hypoxia in the mid and upper basins and degraded benthic animal habitat.
- The mid and lower basins of the Quashnet Estuary can support deployment of oyster aquaculture; however salinity stratification in the mid basin was found to result in salinities <3ppt with consequent high mortality and negligible growth of oysters in surface bags. Oysters in bottom racks at all sites and surface bags in the lower basin showed high survival and high growth rates as waters were generally >10ppt and there was adequate food availability (e.g. POC and phytoplankton levels were high).
- Oysters grown in surface bags at salinities >10 ppt had higher growth rates than oysters grown in bottom trays, possibly due to biofouling of bottom trays.
- While there is shoaling in the region of the tidal inlet, it appears that there is only a minor reduction in tidal exchange through the inlet as seen in tide gauge records.
- The Meadow Neck Road Bridge does not appear to be restricting tidal flows between the upper and lower basins of the estuary as seen in tide gauge records.
- Volumetric exchange between Waquoit Bay and the Quashnet Estuary is basically unchanged in the 2016 analysis compared to the results of the MEP studies (tidal prism in in 2016 = 2003), indicating that the shoaling has not resulted in a gradual continuing restriction of tidal flows.
- If dredging is conducted it should only be in the region of the shoals at the tidal inlet.
- Overall, it appears that there has been an increase in nitrate (31%) and TN (9%) load discharged from the Quashnet River to the receiving estuarine waters since the initial analsis in 2003. The most likely cause is a combination of increased watershed loading and/or alteration of the berm separating the cranberry bogs from the river. This trend toward increase nitrogen loading is consistent with the continuing degradation of nutrient related water and habitat quality within the Quashnet/Moonakis River Estuary.

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