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

Massachusetts
Department of
Environmental
Protection

MEP Technical Memorandum
Final

To: **Rick Dunn, Supervisor, Div. of Watershed Management, DEP**
Steve Halterman, Environmental Eng., Div. of Watershed Management, DEP

From: **Dr. Brian Howes, Technical Director MEP**
Dr. David White, Wetland Specialist MEP
Roland Samimy, Technical Coordinator MEP

RE: **Cockle Cove Salt Marsh Nitrogen Threshold.**

Date: **November 30, 2006**

Overview:
The present DEP/SMAST Massachusetts Estuaries Project Technical Memorandum provides an analysis of the appropriate Nitrogen Management Threshold for Cockle Cove Creek Salt Marsh System, Chatham MA. Cockle Cove Creek is a component sub-system to the Sulphur Springs/Bucks Creek embayment system, which previously underwent the MEP Linked Watershed-Embayment Management Modeling and Assessment Approach and Nutrient Threshold Technical Report process (MEP Dec. 2003)[1]. Cockle Cove Creek is the primary recipient of treated wastewater effluent from the Town of Chatham's WWTF, which discharges to the aquifer near the freshwater stream which forms the headwaters of the central salt marsh creek. As part of the present effort the MEP watershed nitrogen loading was updated (April 2006).

The previous MEP analysis of Cockle Cove Creek within the Bucks Creek/Sulphur System, indicated that Bucks Creek and Sulphur Springs were presently showing habitat impairment due to nitrogen over enrichment from their associated watershed. In contrast, Cockle Cove Creek was functioning as a tidal salt marsh system with tidal exchange with Nantucket Sound through Bucks Creek. MEP analysis of this marsh indicated a healthy salt marsh system with no significant macroalgal accumulations within its creeks. The emergent salt marsh was well vegetated both on the marsh plain and along the creek banks. Presence of macro-invertebrates (*Geukensia, Uca*)

---

[1] Howes, B.L., R.S. Samimy, D.R. Schlezinger, S. Kelley, J. Ramsey, E.Eichner. 2003. Linked-Embayment Model to determine critical nitrogen loading thresholds for Stage Harbor, Sulphur Springs, Taylors Pond, Passing Harbor and Muddy Creek, Chatham, MA. Final Technical Report for the Commonwealth of Massachusetts Department of Environmental Protection, Massachusetts Estuaries Project, 246 pp.

appeared to be similar to other Cape Cod salt marshes, but was not quantified. However, the Chatham Water Quality Monitoring Program data showed high levels of total nitrogen and dissolved inorganic nitrogen (nitrate+ammonium), 2.865 mgN L^{-1} and 0.245 mgN L^{-1}, respectively, in mid marsh. Based upon the observations of the salt marsh habitats and the relative insensitivity of salt marshes to high rates of nitrogen loading, the MEP Technical Team determined that the salt marsh was not currently above its critical nitrogen threshold level (i.e. the nitrogen level supportive of healthy habitat). However, there was insufficient information from which to determine how much additional nitrogen Cockle Cove Creek might be able to tolerate without becoming impaired. There were also concerns that increasing the nitrogen loading to Cockle Cove Creek would further impair or impede restoration of Bucks Creek/Sulphur Springs sub-embayments. Therefore the decision was taken to hold the nitrogen level in Cockle Cove Creek at the existing level and to focus nitrogen management on the adjacent sub-embayments, for planning purposes.

Subsequent to the previous MEP technical effort, the Town of Chatham requested that DEP and the MEP Technical Team move forward on an analysis and field data collection program to support the development of a site-specific nitrogen threshold for Cockle Cove Creek. The need arose from the CWMP effort in which the Town is currently engaged. As the Town of Chatham moves forward with its wastewater planning, upgrading the existing WWTF was identified as a principal component for treating the much higher wastewater flows that will be generated by sewering key portions of the Town. As in all municipalities on Cape Cod, disposal sites for treated effluent are critical for planning and implementation efforts.

To support the Town of Chatham's planning effort, DEP with the MEP Technical Team (SMAST) and MCZM designed and implemented a field data collection program for the summer of 2005 focusing on the nitrogen threshold of Cockle Cove Creek as it relates to future potential wastewater discharge from the WWTF. The MEP Technical Team was supported by the Chatham Department of Health and Environment in the collection of creek water samples. The study was focused on the salt marsh and did not include thresholds for the freshwater stream discharging to the head of the salt marsh. Evaluation of impacts to the nitrogen-enriched Bucks Creek/Sulphur Springs embayments were also excluded, as these loading concerns had been previously described. Field work was conducted by SMAST and MCZM staff. MCZM efforts are described in a detailed survey of the plants on the marsh plain and a [semi-quantitative] survey of invertebrates on the creek bank (see Appendix A). The SMAST portion of the study was to fully map the emergent salt marsh vegetation and macroalgal distribution (both emergent marsh and tidal creeks) and quantify the infaunal community in the tidal creeks relative to habitat quality. In addition the present nitrogen levels and transport in the main creek channel were evaluated relative to habitat quality for the purposes of determining what future increase in wastewater-derived nitrogen concentrations in Cockle Cove Creek might be allowable and still be protective of this resource. By its nature this study provides both a baseline from which to monitor future changes in habitat should they occur and a demonstration of the high tolerance for nitrogen by salt marshes.

The information is presented under the following sections:

I. Present N Related Ecological Health of the Cockle Cove Salt Marshes
II. Freshwater Inflow and Nitrogen Transport within the Cockle Cove Salt Marsh
III. Cockle Cove Salt Marsh Nitrogen Management Threshold

The approach is to summarize key data sets related to critical elements of nitrogen related habitat quality to support on-going efforts in the Bucks Creek/Sulphur Springs sub-embayments. A detailed analysis and interpretation is beyond the scope of this effort.

Background Nitrogen and Salt Marshes:
Salt marshes, like Cockle Cove Creek, have extensive emergent vegetated areas and tidal creeks which have virtually complete flushing on each tide. The result is a high assimilative capacity for nitrogen, particularly when compared to shallow coastal embayments (e.g. Stage Harbor). The greater sensitivity of embayments versus wetlands results from their lower tidal exchange rates, the fact that there is not exposure of the sediments to the atmosphere at low tide (like the marsh plain), and the fact that these systems have evolved under much lower levels of productivity and organic matter loading than wetlands. For example, the organic carbon content of New England Salt Marsh vegetated sediments can frequently reach 20%, while embayment sediments are generally in the 1%-5% range. Similarly, oxygen depletion in the creeks of *pristine* wetlands can occur on summer nights, while embayment bottomwaters become hypoxic generally as a result of *eutrophic* conditions.

Some additional insight into the nitrogen response by salt marshes can be garnered from long-term chronic nitrogen addition experiments. These have been conducted at multiple sites along the Atlantic coast and specifically in Great Sippewissett Marsh (West Falmouth, MA). This latter project has been conducted by WHOI scientists since 1970 and solely by current SMAST Staff since 1985. These studies reveal that nitrogen additions to *Spartina alterniflora* areas typically results in increased plant production and biomass and secondary production as well. Nitrogen dynamics have been quantified, which show that as nitrogen is added the initial increase in N input is taken up by the plants, but this plant demand is rapidly satisfied and additional load is denitrified *in situ* by soil bacteria. In the Great Sippewissett Marsh fertilization experiments the denitrification capacity of the sediments has not been exhausted in 30 years of N additions and at levels about 7 times the natural background N input (75.6 g N m^{-2} each growing season).

Salt marsh creek bottoms and creek banks have also developed under nutrient and organic matter rich conditions, as have the organisms that they support. It is the creekbottoms rather than the emergent marsh which is the primary receptor of increased watershed derived nitrogen in Cape Cod salt marshes. Watershed nitrogen predominantly enters these salt marshes through groundwater or small headwater streams. Both surface and groundwater entry focuses on the tidal channels. Even groundwater entry through seepage at the upland interface is channeled to creek bottoms. As the tide ebbs in these salt marshes (like Cockle Cove Creek) the freshwater inflow freshens the waters and the nitrogen levels in the tidal creeks increase due to the nitrogen entry from the watershed. At low tide the nitrogen levels in the tidal creeks are dominated by watershed inputs.

Since the predominant form of nitrogen entering from the watershed is inorganic nitrate, the effect on the creek bottom is to stimulate denitrification, hence nitrogen removal. In a salt marsh in West Falmouth Harbor, Mashapaquit Creek, ~40% of the entering watershed nitrogen is denitrified by the creekbottom sediments on an annual basis. This stimulation of denitrification does not negatively affect the salt marsh, but does result in a reduction of nitrogen loading to the adjacent nitrogen sensitive coastal waters. However, analysis by MEP Staff of salt marsh areas receiving wastewater discharges does appear to indicate that at higher nitrogen loads, macroalgal accumulations can occur. These accumulations are generally found in the creek bottoms and flats and also may drift and settle on the creekbanks. Large macroalgal accumulations in tidal creeks can cause impairment of benthic animal communities. In the latter case, negative effects on creekbank grasses can occur, which may lead to bank erosion and negative effects on organisms.

The assessment of Cockle Cove Creek focused on determining the spatial distribution of the salt marsh habitats and their health. There was particular emphasis on macroalgal accumulation in the creek bottoms and along creek banks, as it is these accumulations that are considered to be the primary indicator of negative impacts to the marsh from nitrogen loading.

I. Present N Related Ecological Health of Cockle Cove Salt Marshes

A. Cockle Cove Creek Data Collection: The following is a brief description of the data collection efforts to support nitrogen analysis within the salt marshes of Cockle Cove Creek. Assessment of upgradient freshwater wetlands and downgradient receiving embayments was not included. The effort was focused on 3 subsystems of the marsh:

- Vegetated Marsh Plain (Section IB, Appendix A)
- Creek Bottom and Creek Bank (Section IC)
- Watercolumn (Section II)

Vegetated Marsh Plain – the primary purpose of this effort was to determine the general extent of high salt marsh (*Spartina patens*, *Distichlis spicata*, etc.), low marsh (Tall and short form *Spartina alterniflora*) and to a lesser extent the brackish marsh (*Scirpus*, *Phragmities*, etc). The tasks included:

- general mapping of the major plant zones (aerial photo and site survey)
- determination of the production/health of the various salt marsh plant zones (by height and density and % cover)

- determination of extent of bare areas on the marsh plain

General mapping was performed by SMAST staff with the spatial distribution of vegetation patches larger than 4m x 4m being determined. Plant characteristics were assayed by MCZM (B. Carlisle, J. Smith) along fixed transects. Both efforts also noted macroalgal abundance.

Creek Bottom and Creek Bank – This marsh component is the most likely to be effected by increased N loading. The primary issue was to determine:

- *Macroalgae in creek bottoms*. Macroalgal accumulations within the creek bottom and flats of Cockle Cove Creek from the headwaters to the discharge channel to Bucks Creek were mapped. This occurred during the interval of likely maximum accumulation. The survey focused on identifying any areas of accumulation, density of algae and species. Seven surveys were conducted during June – October.
- *Macroalgae on creekbanks*. The occurrence of macroalgae drifting on to creek bank vegetation was also assessed. Seven surveys were conducted during June – October.
- *Creekbank vegetation health*. The vegetation surveys also included creek bank areas and measures of plant height % cover. The surveys and measures served as indicators of plant community health and were collected during August 2005.
- *Invertebrate fauna*. The dominant salt marsh invertebrates present are a good estimate of system health. A survey of the dominant creek bank macrofauna was undertaken in August 2005 (MCZM) and the creekbottom infauna community in July 2005 (SMAST). The goal of these surveys was to determine the general nutrient related health of the various communities.

The MCZM protocols for the plant survey were consistent with those in the U.S. Environmental Protection Agency-approved Cape Cod Salt Marsh Ecological Assessment Project Quality Assurance Project Plan: FINAL June 5, 2000, Massachusetts Coastal Zone Management. The benthic infaunal survey and nitrogen studies were consistent with the Massachusetts Estuaries Project Quality Assurance Project Plan as accepted by MA Department of Environmental Protection and USEPA.

B. Habitat Assessment of Cockle Cove Creek (Vegetated Marsh Plain)

Plant Communities Emergent Marsh - The overall distribution of plant communities were mapped during the summer of 2005. The goal was to determine the predominant plant communities (i.e. species mixes) and their spatial pattern. Bare areas were also mapped and areas of accumulation of macro-algae were sought for sampling and analysis. Mapping data was integrated into GIS to allow for the calculation of coverage area.

Cockle Cove Creek salt marsh is a typical New England "pocket" marsh, comprised of a single tidal inlet and a central tidal creek. The vegetation is also typical, with 73% of the emergent marsh being vegetated by *Spartina alterniflora, Spartina patens* or a mixture. Also typical is the high marsh community (*Spartina patens, Distichlis spicata* and *Juncus gerardi*) which occupies much of the remaining area (Figure 1, Table 1). The predominance of Spartina alterniflora indicates that this system interacts with the offshore coastal waters, as it is routinely flooded at high tide. The lack of macroalgal accumulations and few pannes and bare areas indicate a healthy plant system.

The MCZM investigation further supports the contention of a healthy emergent salt marsh (Appendix A). This study examined the plants found along 12 transects throughout the salt marsh to determine the diversity of plant species within the system and their relative "health". MCZM concludes that the Cockle Cove Creek marsh "has a particularly high level of plant diversity for a salt marsh system which can be attributed to large numbers of brackish and terrestrial border species. Much of the marsh perimeter seems to be the interface for local water table, creating fresher edges where species like *Typha angustifolia, Scirpus pungens, Scirpus robustus,* and *Spartina cynosuroides* hold their niches. In addition, there are areas on the upper marsh plain behind the former dike (landward section including transects 1-4) where marsh elevation is obviously higher and supports salt marsh terrestrial border species like *Solidago sempirvirens, Agropyron pungens, Panicum virgatum*, and *Festuca rubra*. No floating algal mats occurred in the survey plots, although a couple small mats were seen on the marsh plain and would not be considered to be of concern. "

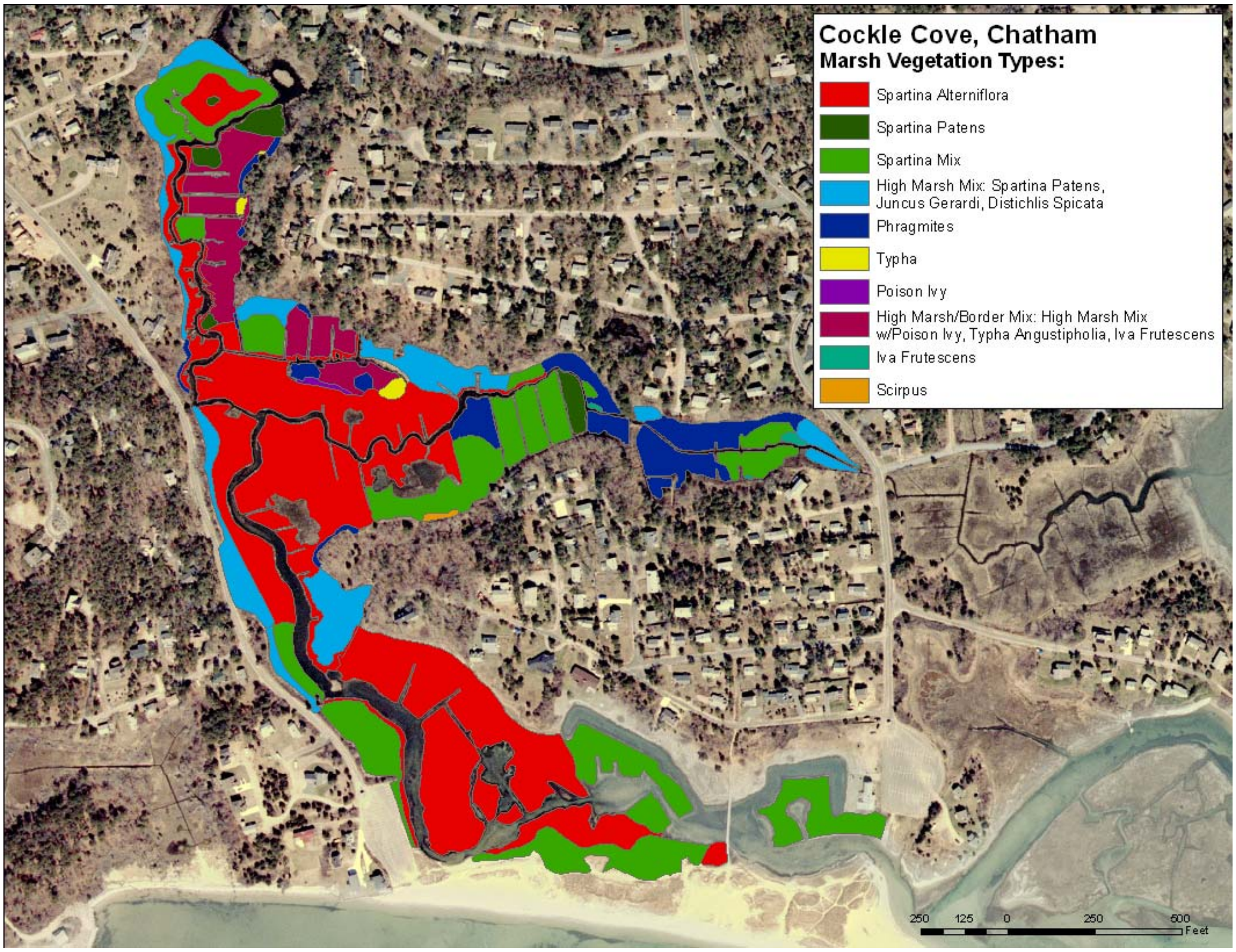


Figure 1. Plant distribution within the estuarine reach of Cockle Cove Creek. The wetlands system is dominated by low (Spartina alterniflora) and high (Spartina patens or Mix) salt marsh types.

Table --.1. Wetland types and areas comprising the estuarine reach of Cockle Cove Creek, Chatham MA. Analysis based upon field mapping by SMAST, summer 2005.	
Marsh Type	**Total Area (acre)**
High Marsh Mix: *Spartina patens, Juncus gerardi, Distichlis spicata*	3.13
High Marsh/Border Mix: High Marsh Mix w/Poison Ivy, *Typha angustipholia, Iva frutescens*	2.04
Iva Frutescens	0.06
Phragmites	2.16
Poison Ivy	0.05
Scirpus	0.04
Spartina Alterniflora	12.28
Spartina Mix	7.29
Spartina Patens	0.55
Typha	0.11
Total Vegetated Area	**27.71**
Creekbottom	5.02
Total Wetland Area	**32.73**

Overall, the results of the prior MEP analysis, the SMAST vegetation survey marsh-wide and the detailed MCZM survey all support the contention that the emergent marsh within Cockle Cove Creek is presently healthy and not degraded. This is based upon the lack of macroalgal accumulation, and the absence of bare areas or plant die-back. In addition, although Phragmites is present at the upland border, it occupies only a small area of wetland, most likely due to the high flooding frequency of most of the marsh plain. These results also form the basis for assessment of future changes within the emergent marsh area as management alternatives are implemented.

C. Habitat Assessment of Cockle Cove Creek (Creek Bottom and Creek Bank)

<u>Plant Communities, Macroalgae</u> - Macroalgae were surveyed during the mapping of the emergent marsh and on each occasion of sampling of the creek bottoms. Figure 3 shows the locations in the marsh where samples were taken. As depicted in Figure 2, the creek bottom represents ~5 acres of salt marsh or about 1/6th of the total salt marsh area. Macroalgal accumulations have been noted in other salt marshes with high levels of nitrogen input, e.g. Mashapaquit Creek and Aucoot Cove. The primary macroalgae was Ulva (sea lettuce), which accumulated in the lower reaches of the tidal creeks and also on the creek bank grasses. The effect is to degrade the habitat for infaunal and disturb the growth pattern of the grasses, potentially resulting in erosion.

In both the MCZM survey and in the multiple SMAST surveys, no significant macroalgal accumulations were found. Macroalgae that were observed were generally sparse and had drifted into Cockle Cove Creek on the incoming tide from Bucks Creek. Generally the creek bottom was free of macroalgae and the creek banks did not show accumulations or resulting die off. On the emergent marsh macroalgae were generally found in the wet pannes, as is normal for New England salt marshes. In the tidal creek, macroalgae was observed primarily in the lowest reach (4), within the dredged lagoons adjacent the residential area. These accumulations were not large and appeared to result from macroalgae entering on the incoming tide, as was observed in the August 3, 2005 tidal study (Section II). Macroalgae (several grams) were collected from both the emergent salt marsh and the tidal creeks for analysis (Figure 3, see Section II), but it was difficult to find.

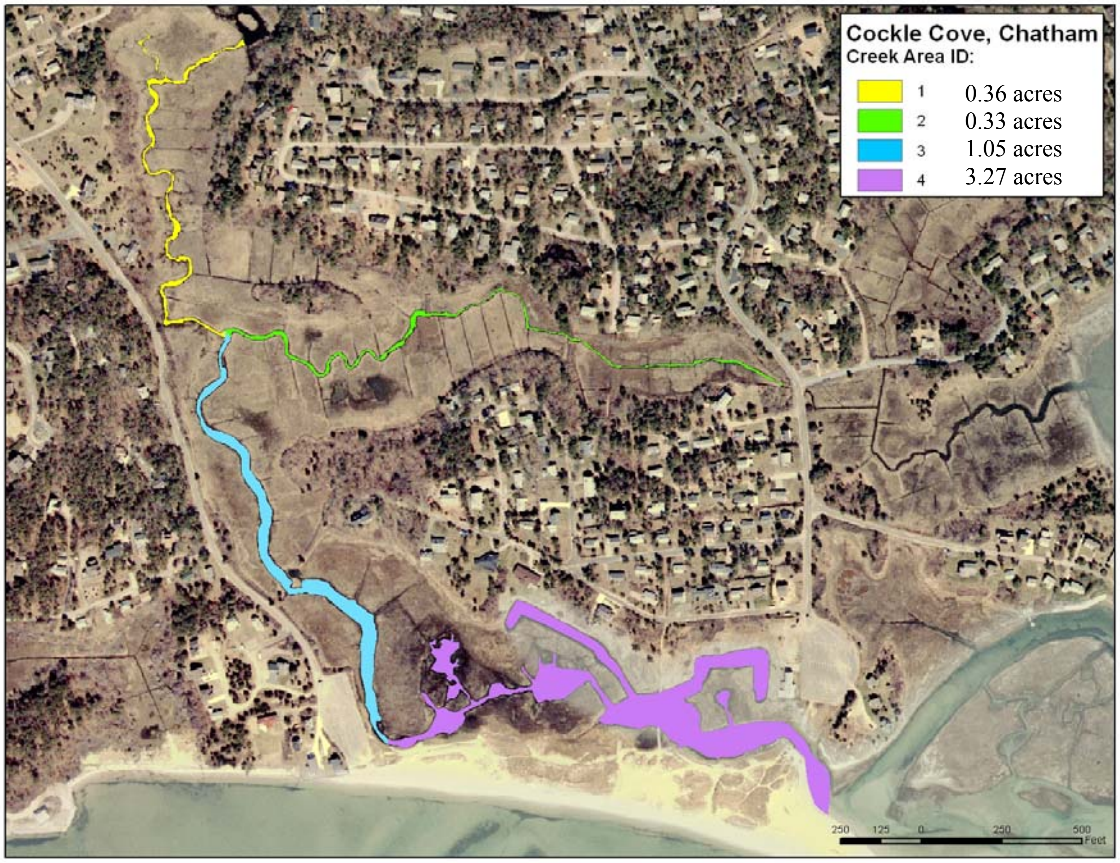


Figure 2. Cockle Cove Creek main tidal channel reaches. The 4 reaches likely have different effects on nitrogen transport through the system, due to their different nitrogen levels and different substrate characteristics (sand, mud).

Figure 3. Locations of macroalgal sample collection.

Benthic Animal Communities - The density and distribution of the major invertebrates was assessed along the creek banks and in the creek bottom areas. Analysis of the marsh plain was not undertaken, as there was no evidence of impairment and the marsh plain is not a primary recipient of watershed nitrogen inputs. In addition, the marsh plain is highly tolerant of nitrogen input. The creek banks and creek bottoms are most likely to be impacted by increased nitrogen loads, but only through the proximate mechanism of increased algal accumulation (i.e. nitrogen itself is not harmful to these communities).

The creek bank survey conducted by MCZM (Appendix A) surveyed four taxa of macroinvertebrates. "The most common was the marsh snail, *Melampus bidentatus* (73.1%), with the ribbed mussel, *Geukensia demissa* (24.4%), essentially comprising the rest of the invertebrate community. Several individual isopods and fiddler crabs (either *Uca pugilator* or *Uca pugnax*) were surveyed. It is important to note that the survey was on the marsh surface and vegetation only and did not include substrate removal. There was significant evidence of Uca burrows, but the presence of crabs in each burrow was not part of the scope of work and was not determined. The taxa list, total and percent total abundance values are listed in Table 2" of Appendix A. *Melampus* is an important prey species for fish and some avian species as is *Uca* and smaller life stages of *Geukensia*. There was no indication of impairment in this survey and the dominant species are typical of healthy Cape Cod salt marshes. These results are consistent with the observed health of the creek bank grasses and the absence of macroalgal accumulations along the creek banks.

The creek bottom survey conducted by SMAST included duplicate samples taken from 7 sites along the main creek and its tributary (Figure 4). Results indicated a highly productive and diverse benthic infaunal community (Table 2). The numbers of individuals per 0.0625 m^2 sample were frequently in excess of 1000 and sometimes >2000. Similarly the species richness (number of species-column 2) was generally ~10 with a diversity index (H') ~2. The species were dominated by polychaetes and crustaceans, with some mollusks. It should be noted that the dominant species (*Leptocheirus, Paranais*) were also dominants in a study of a healthy salt marsh, Great Sippewisset Marsh[2].

Analysis of the evenness and diversity of the benthic animal communities has been evaluated by the MEP for tidal embayments. The evenness statistic can range from 0-1 (one being most even), while the diversity index does not have a theoretical upper limit. Highest quality habitat areas, as shown by oxygen and chlorophyll records and eelgrass coverage, generally have the highest diversity (generally >3) and evenness (~0.7). The converse is also true, with poorest habitat quality found where diversity is <1 and evenness is <0.5. While these levels do not directly relate to salt marshes, due to their higher natural organic loading, they can be used as a reference point. If this issue is

---

[2] Wiltse, W.I., K. Foreman, J.M. Teal and I. Valiela. 1984. Role of Predators and food resources n regulating the macrobenthos of salt marsh creeks. J. Marine Research 42:923-942.

kept in mind and the spatial pattern of numbers and diversity is examined, a clear pattern emerges in Cockle Cove Creek.

In Cockle Cove Creek there was a trend toward lower diversity and numbers in the upper versus lower marsh, most likely related to the soft organic muds typical of inner areas of salt marshes on Cape Cod. However, there was an absence of stress indicator species, such as *Capitella* and *Streblospio* (Table 3). The number of individuals was relatively high (~1000), as was the diversity (H'), generally ~2. The evenness was moderate, generally between 0.5-0.9. Based upon the creek bottom survey data, it appears that the creek bottom infaunal community is presently healthy. This is consistent with the absence of macroalgal accumulation in this highly tidally flushed salt marsh creek. It is likely that the creek bottom environmental quality is also related to the near complete "draining" of the tidal creeks during each low tide, which serves to lessen the occurrence of any low oxygen events in the overlying waters.

Figure 4. Locations of sampling of benthic infaunal communities within the creekbottoms of Cockle Cove Creek.

Table 2. Cockle Cove Creek salt marsh creekbottom invertebrate infaunal collected July 28, 2005 by Coastal Systems Program Staff (SMAST). Samples were collected using a 0.0625 m^2 Young modified Van Veen Grab Sampler. Station locations refer to Figure 4.

Location	Total Actual Species	Total Actual Individuals	Species Calculated @75 Indiv.	Weiner Diversity (H')	Evenness (E)
Cockle Cove Creek					
Sta. 1	11	802	4.48	1.61	0.47
Sta. 1D	13	1244	5.00	1.74	0.47
Sta. 2	14	2352	8.78	2.46	0.65
Sta. 2D	13	2396	10.05	2.43	0.66
Sta. 3	11	1212	7.79	1.95	0.56
Sta. 3D	9	984	7.26	1.86	0.59
Sta. 4	12	726	5.91	1.86	0.52
Sta. 4D	8	651	6.64	1.94	0.65
Sta. 5	9	1296	7.55	2.22	0.70
Sta. 5D	9	3200	6.52	2.09	0.66
Sta. 6	8	648	7.21	2.34	0.78
Sta. 6D	6	536	5.91	2.35	0.91
Sta. 7	7	1256	6.62	2.41	0.86
Sta. 7D	7	1481	6.03	2.26	0.81

Table 3. Dominant species of benthic infaunal in Cockle Cove Creek tidal channels. Only species accounting for 1% or more of the total individuals found are presented.

Group	Species	Dominance
Crustacea	*Leptocheirus plumulosus*	39%
Polychaeta	*Paranais littoralis*	20%
Polychaeta	*Melinna cristata*	15%
Polychaeta	Tubificoides sp. 1	9%
Crustacea	*Cyclaspis varians*	5%
Crustacea	*Gammarus fasciatus*	2%
Crustacea	*Cyanthura polita*	2%
Crustacea	*Edotea triloba*	2%
Crustacea	Tanaidacea sp. 1	2%
Crustacea	*Gammarus mucronatus*	2%
Polychaeta	*Mediomastus californiensis*	1%

II. Freshwater Inflow and Nitrogen Transport within Cockle Cove Salt Marsh (Water Column Evaluation)

Freshwater inflows to the Cockle Cove Salt Marsh were evaluated using (a) water balance derived from the MEP watershed delineation and recharge from precipitation and WWTF infiltration, (b) measured freshwater inflows from the headwater stream and within the marsh creek, (c) measured freshwater discharge through the tidal inlet over a tidal cycle and (d) USGS modeling of the fate of future WWTF effluent discharges. These data and modeling outputs were developed with the Town of Chatham, the Cape Cod Commission and the USGS.

In parallel with the habitat assessments (Section I), SMAST, with the assistance of the Chatham Water Quality Laboratory, undertook an analysis of nitrogen levels and transport within Cockle Cove Creek (Figure 5). In addition to diffuse watershed nitrogen inputs, Cockle Cove Creek is the primary recipient of treated wastewater effluent from the Town of Chatham's WWTF that discharges to the aquifer near the freshwater stream which forms the headwaters of the central salt marsh creek. Data collection included measurement of nitrogen mass flux and concentration at multiple points along the tidal channel during low tide. These data were used for assessment of the total nitrogen mass flux to Bucks Creek, the determination of nitrogen concentrations available to benthic algae and the present rate of nitrogen removal from the salt marsh prior to discharge to Bucks Creek. The biweekly surveys were supplemented by a tidal study near the outlet from Cockle Cove Creek to Bucks Creek. In conducting the tidal survey the total import and export of nitrogen was determined over a complete tidal cycle, taking into consideration analysis of water column nitrogen and macroalgae for $^{15}N/^{14}N$ ratio (called $\delta\ ^{15}N$) as an indicator of wastewater nitrogen (see part B, below).

During the summer of 2005, current velocity measurements were made and water samples were collected during the interval 1 hour before slack low tide at multiple points from the headwaters through the marsh to the outlet at Bucks Creek (Figure 5). Water samples were analyzed for nitrogen concentrations (DIN, DON, PON). As part of this effort, the MEP watershed nitrogen loading was updated (April 2006).

A. Freshwater Inflow.

It should be noted by the reader that freshwater analysis (volumetric inflow or spatial distribution) was not part of the SMAST Cockle Cove Study. This section was added based upon concerns raised by the Draft Technical Memorandum to assist the Town of Chatham and MassDEP evaluate potential future issues related to increased freshwater inflow to this system resulting from potential increased WWTF discharges within its watershed. It is not meant as a complete analysis, but does serve as a guide for evaluating future changes in inflow. As work is continuing relative to future WWTF effluent disposal, it is certain that this analysis will need refinement in the coming years.

Total freshwater inflow to Cockle Cove Creek was previously determined by the MEP Technical Team based upon the watershed area, precipitation and recharge. This represents a long-term average freshwater inflow to the Creek of 2335 m^3 d^{-1} or 614,000 gpd. This value agrees well with the net total freshwater outflow through the tidal inlet measured during the tidal study (August 2005), 2420 m^3 d^{-1} or 637,000 gpd (Table 4). This latter measurement accounts for both tidal inflow and outflow of freshwater that occurs over a complete flood/ebb cycle, based upon measurements of flow and salinity at 0.5 hr intervals. However, neither of these estimates yields information on the spatial distribution of freshwater inflow to this system. To gain insight into the spatial distribution of freshwater entry to the creek system, flow and salinity measurements collected as part of the nitrogen flux study were used to determine freshwater discharges at 6 locations (CC-1, 2, 3, 4, 4a, 5) within the stream/marsh creek (Figure 6).

Freshwater flow during ebb tide in the main tidal creeks showed a pattern typical of tidal marshes in New England. A single freshwater stream discharges to the headwaters of the main tidal creek. Moving down the main tidal creek, additional freshwater volume is encountered due to "pick-up" from groundwater discharge. It appears that two thirds or more of the freshwater inflow occurs within the upper portion of the marsh (above CC-3). In addition, it is clear that the eastern tributary creek is not receiving significant amounts of freshwater inflow. Daily discharge was calculated from the ebb tide data based upon a 20 hr groundwater seepage duration to the tidal creeks and a 24 hr discharge from the entering surface water stream. Unfortunately, estimating the total freshwater outlfow (CC-5) was difficult due to the relatively high salinities. While waters at all sites required adjustment for mixing with seawater, the high salinities at the lowest site introduce an additional source of measurement error. Examining the mid-marsh (CC-4A) and the outlet flows relative to the MEP watershed model and tidal study results shows a relatively constrained value for freshwater inflow (Table 4) and supports the long-term average value of long-term average freshwater inflow to the Creek of 2335 m3 d-1 or 614,000 gpd. The long-term value and spatial discharge information will be used to evaluate potential issues related to future increased freshwater inflows.

An additional point related to the eastern tributary, it appears that the *Phragmites* in this region is not directly related to freshwater inflow as much as elevation and possibly tidal restriction (upper most reach between Cockle Cove and Sulfur Springs). In any case, the regions with the highest freshwater inflow do not seem to support the greatest coverages of *Phragmites* at the present time (Figure 1). Despite this observation, significant increases in freshwater discharge to the marsh can sometimes result in expansion of *Phragmites* areas or a shift from salt marsh plants to more brackish or even freshwater forms. Given this real concern, the MEP Technical Team assembled the available information on existing and potential future freshwater inflows. Future increases in freshwater inflow stem almost entirely from increased effluent discharges from expanding the present WWTF to support the sewer system expansion within the Town of Chatham for estuarine restoration.

Based upon information provided by Dr. R. Duncanson (Town of Chatham) and groundwater modeling by the USGS to support the Town of Chatham's on-going planning effort, the MEP Technical Team moved forward with 2 scenarios of increased effluent discharge. The first was to increase effluent discharge at the existing site to 0.4 MGD. The second followed the 0.4 MGD with a further 1.1 mgd discharge at Site #1 also within the Cockle Cove Creek watershed (Figure 5). The USGS particle tracking model has limitations which cause difficulties in accurately determining where groundwater will discharge in these situations and often shows groundwater going under surface water bodies and discharging directly to offshore waters. While this occurred in the present case, it was the consensus of all parties that it is more accurate (and also environmentally conservative) to discharge this underflow into the associated estuary (Table 5). This interpretation of the modeling results will be addressed with further future modeling.

It is interesting that the higher flow scenario, 0.4 MGD at present site plus 1.1 MGD at Site #1, did not result in significantly higher freshwater inflow rates to Cockle Cove Creek than increasing the discharge at the present site to 0.4 MGD alone. This results from the mounding of the groundwater at the present site serving to "redirect" flow from Site #1 to other coastal sites. While this may reduce potential freshwater effects on Cockle Cove Creek, its effect on the other estuaries of Chatham will need to be assessed.

It appears that increasing the effluent discharge within the watershed to Cockle Cove Creek will result in a large increase in freshwater inflow to this system, ~50% greater than present. In fact, the present WWTF discharge increased the pre-WWTF freshwater inflow by 17%. It is unlikely that this will have an effect on the creek bottom community. The projected future freshwater inflow is still small relative to the tidal prism (~15,000 m^3d^{-1} vs 3,600 m^3d^{-1}) which will not support a significant shift in the tidal water salinity (the proximate cause of community shift). In contrast, the increase freshwater inflow is relatively large compared to the total freshwater balance. Therefore in regions where groundwater is focused locally on the emergent marsh, effects may be seen. For example, should seepage at the upland/marsh plain interface increase significantly due to the water table changes and the 50% increase in flow, then there may become a localized plant community shift. However, it should be noted that there is no evidence that the previous increase in freshwater inflow (from bringing the present WWTF on-line) resulted in plant community shifts. If shifts had occurred they would have been seen in the uppermost reaches of the main tidal creek basin, where there is presently a prevalence of salt marsh species. Therefore, the concern remains speculative.

If freshwater inflow effects on the marsh plain were to become an issue, construction of marsh cells at the upland edge to intercept freshwater discharge might be considered. The construction of such cells has been previously proposed to mitigate nitrogen inputs, but they would serve to re-route freshwater, as well.

Table 4.

Estimates of watershed freshwater inflow to Cockle Cove Creek. Values are m3/d and (1000gpd, 1000's of gallons per day)				
		Freshwater Inflow m3/d (1000gpd)		
Location	ID	Ebb Tide	Tidal Cycle	Watershed
Upper Stream	CC-1	480 (126)	--	--
Marsh Head	CC-2	875 (230)	--	--
Mouth Main Stem	CC-3	1900 (553)	--	--
Mouth East Tributary	CC-4	190 (50)	--	--
Mid Marsh	CC-4A	1930 (508)	--	--
Marsh Outlet	CC-5	3050 (803)	2420 (637)	2335 (614)

* Groundwater inflow based upon 20 hr per day seepage.

Table 5.. Increased freshwater inflow volumes to Chatham Estuaries based at Town-wide sewering and 2020 well pumping with discharge to existing WWTF site and Site #1. Modified from USGS Scenario #2 particle track modeling for the Cape Cod Commission and the Town of Chatham.

	1.1 MGD @ Site #1		0.4 MGD @ WWTF Site		Total 1.5 MGD
Embayment	Flow_gpd	Adjusted Flow_gpd	Flow_gpd	Adjusted Flow_gpd	**Adjusted Total Flow gal/d**
Pleasant Bay Basins	70,089	70,089	0	0	70,089
Stage Harbor System	1,524	2,994	0	0	2,994
Taylors Pond/Mill Creek System	301,688	592,728	0	0	592,728
Sulfur Springs/Bucks Creek	199,602	392,158	0	0	392,158
Cockle Cove Creek	**15,237**	**29,936**	**387,518**	**400,018**	**429,954**
Offshore Nantucket Sound	499,766	0	12,501	0	0

Underflow to Nantucket Sound was apportioned to the south facing embayments.

Table 6. Present freshwater inflow to Cockle Cove Creek and projected future increases from additional WWTF effluent discharges at the present WWTF site and an additional site "#1". The projected additional inflows are based upon the USGS particle tracking model results, reproduced below.

Freshwater Source	Inflow Volume to CC Crk		% Increase over present inflow
	m3/d	1000's gpd	
Existing Watershed:			
Total Inflow *	2335	614	--
Non-WWTF	1923	506	--
WWTF	410	108	--
Additional WWTF Discharges:			
Increase WWTF to 0.4 MGD **	1520	400	**48%**
Increase WWTF to 0.4 MGD + Site #1 Discharge 1.1 MGD **	1634	430	**52%**

* Long-term average inflow from watershed-groundwater model.

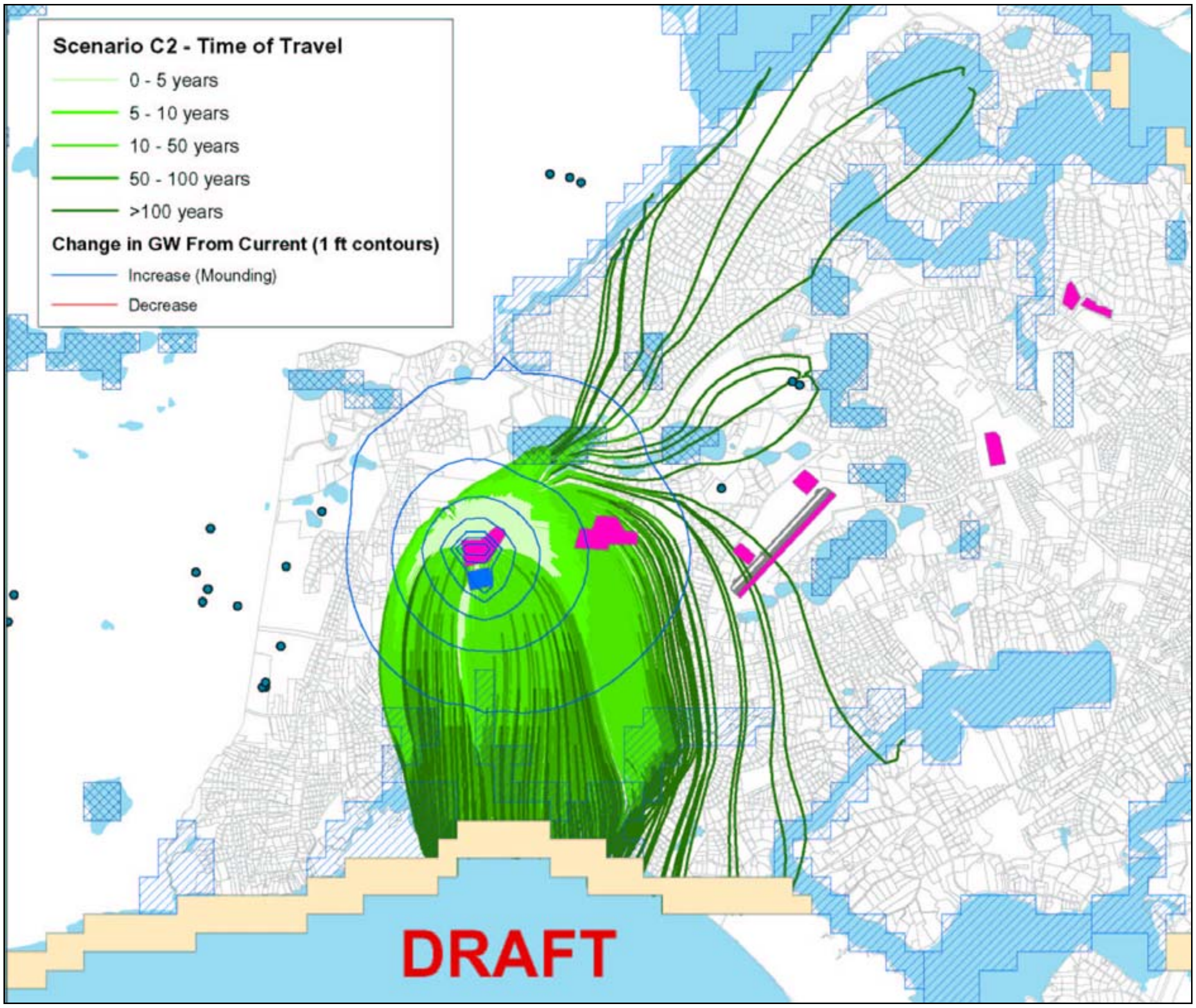


Figure 5. Groundwater particle track modeling of potential future WWTF effluent disposal at the existing WWTF site (0.4 MGD) and an adjacent site "#1" (1.1 MGD) by the USGS with the CCC (Scenario #2 6/23/04). This full Town sewered with 2020 well pumping scenario was presented by the Town of Chatham to the MEP for the present evaluation. Figure provided by the USGS to the Town of Chatham.

B. Nutrient levels, flux and attenuation.

Cockle Cove Creek receives nitrogen input from its watershed, including treated effluent from disposal at the Town of Chatham WWTF, as well as the atmosphere. The result is high levels of nitrogen in ebbing tidal water from Cockle Cove Creek to Bucks Creek. Levels of inorganic nitrogen, nitrate and ammonium, in the fresh headwaters to the estuary averaged 1.791 mg N L^{-1} and 1.104 mg N L^{-1}, respectively and total nitrogen (TN) at 3.154 mg N L^{-1} (Stations CM-J, CC 2, Table 7). These values contrast strongly with the offshore inflowing waters which typically have TN values <0.3 mg N L-1 and which are dominated by organic nitrogen forms, rather than the predominance of inorganic nitrogen forms (>90%) in the fresh water inflows.

While the high level of inorganic nitrogen is anticipated in freshwater systems, due to their limitation of plant growth by available phosphorus (primarily ortho-phosphate), the high nitrogen levels in Cockle Cove Creek were also observed in the ebbing tidal creek waters. It appears from the water quality data (Table 7) that algal production on the tidal creek bottom is not limited by nitrogen or phosphorus, as the levels of inorganic N and inorganic P remain above 0.3 mg N L-1 and 0.03 mg P L-1 from the headwaters to the outlet to Bucks Creek. These are very high concentrations, which are well above those used to stimulate algal growth. However, macroalgal accumulation was not observed by MCZM, SMAST or Town Staff during their frequent visits to the creek sampling sites.

Nitrogen does appear to be being transformed within the creek waters and sediments as the marsh is exporting particulate organic nitrogen and removing inorganic nitrogen from the waters that pass through it. The biweekly sampling of nitrogen transport showed nitrogen export to Bucks Creek ~46% of that predicted from the MEP watershed land-use model (Table 8). In addition, the ebb tide measurements along the main channel of Cockle Cove Creek were indicative of sediment nitrogen uptake. It should be noted that nitrogen enters the creek from its watershed along its length and therefore declines in nitrogen mass transport between individual locations is less dramatic than if the input were solely from the headwaters.

The tidal cycle study yielded consistent results to the ebb tidal samplings. The tidal cycle study measured both the nitrogen import and export from the salt marsh system, during a neap tide, which would minimize the measured nitrogen attenuation rate. Figure 7 shows that both DIN and Total N concentrations decrease during flood tide as waters from offshore enter the marsh. During tidal ebb, N concentrations increase as creek waters flow out of the marsh. The tidal study also indicated a net export of nitrogen from Cockle Cove Creek to Bucks Creek that is less than the watershed inputs by ~50% (Table 9). Moreover, it appears that in addition to removing nitrogen the marsh is transforming nitrogen from inorganic forms to organic forms. This can be best seen by comparing the average dissolved inorganic nitrogen (DIN) transport through the mid-marsh site (44.21 mg N sec^{-1}, Table 8) with the ebb tide transport of DIN (24.63 mg N sec^{-1}, calculated from Table 9). The export of particulate organic matter is seen in the net export, during the tidal study. These observations are consistent with other salt marshes of similar morphology (i.e. central tidal creek, New England marshes), both in their rates of nitrogen attenuation and in their nitrogen transformations.

Figure 6. Sampling locations for nitrogen concentration and mass transport (boxes) and the tidal study (red line)

Table 7. Water quality parameters collected along the main channel of Cockle Cove Creek, summer 2000-2005. Values are means and standard error (s.e.) and number of samples (N). Transport of nitrogen and phosphate through the Cockle Cove Creek marshes, summer 2005. Station I.D.'s are shown in Figure 5.

Marsh Site	Sta i.d.[a]	Salinity (ppt)			Bioactive N (mgN/L)			Total N (mgLN/L)			Ortho-phosphate (mgN/L)		
		mean	s.e.	N	mean	s.e.	N	mean	s.e.	N	mean	s.e.	N
Fresh Headwater	CM-G/CC 1	0.2	0.02	70	1.514	0.053	61	1.822	0.061	61	0.009	0.001	73
Fresh Tidal	CM-J/CC 2	0.3	0.03	42	2.960	0.050	33	3.154	0.060	33	0.005	0.001	42
Main Channel													
mid-Salt Marsh	CM-F/CC 3	4.4	0.7	70	1.687	0.054	64	1.921	0.058	64	0.054	0.003	75
mid-lower SM	CM-T/4A,B4b	6.7	0.7	32	1.399	0.062	23	1.658	0.073	23	0.067	0.005	32
marsh inlet	CM-12/CC 5	21.9	0.6	95	0.540	0.029	79	0.787	0.034	79	0.038	0.003	95

a - Stations sampled by the Town of Chatham Water Quality Laboratory (Dr. R. Duncanson)/SMAST designated

Marsh Site	Sta i.d.[a]	NOx (mgN/L)			Ammonium (mgN/L)			Part. Org. N (mgN/L)			Dissolved Org N (mg/L)		
		mean	s.d.	N	mean	s.d.	N	mean	s.d.	N	mean	s.d.	N
Fresh Headwater	CM-G/CC 1	0.662	0.02	75	0.732	0.053	75	0.120	0.061	61	0.308	0.027	75
Fresh Tidal	CM-J/CC 2	1.791	0.03	42	1.104	0.050	42	0.066	0.064	33	0.193	0.044	42
Main Channel													
mid-Salt Marsh	CM-F/CC 3	1.201	0.7	75	0.321	0.054	75	0.165	0.059	64	0.234	0.021	75
mid-lower SM	CM-T/4A,B4b	0.875	0.7	32	0.314	0.062	32	0.210	0.073	23	0.259	0.032	32
marsh inlet	CM-12/CC 5	0.219	0.6	95	0.136	0.029	95	0.184	0.37	79	0.247	0.020	95

a - Stations sampled by the Town of Chatham Water Quality Laboratory (Dr. R. Duncanson)/SMAST designated

Table 8. Transport of nitrogen and phosphate through the Cockle Cove Creek marshes through the warmer months of 2005. Values are averages of measured watershed flux through the marsh, based upon bi monthly ebb tide sampling. All values are presented as daily transport (mg/sec) to allow comparison to the MEP Watershed Model (updated April 2006). Station I.D.'s are shown in Figure 5. Data was collected by the Town of Chatham Water Quality Laboratory and SMAST staff.

Marsh Site	I.D.	NOx	NH_4	PON	DON	BioActive N	Total N	PO_4
Freshwater: Headwater Stream								
Fresh Headwater	CC 1	3.13	4.98	0.81	1.85	8.91	10.07	0.004
Fresh Tidal	CC 2	18.75	12.15	0.69	1.16	31.60	32.99	0.004
Main Channel								
mid-Salt Marsh	CC 3	35.65	8.56	2.78	3.82	46.99	50.35	0.153
side channel to CC-3	CC 4	1.04	0.69	1.74	1.39	3.47	4.40	0.028
mid-lower SM	CC 4a	29.86	8.45	4.40	4.51	42.71	46.41	0.205
marsh inlet	CC 5	17.36	9.38	14.00	13.43	**40.86**	**52.43**	0.150
Watershed Land-Use Model N Loading								
Non-WWTF N Load	--	--	--	--	--	--	59.26	--
WWTF N Load	--	--	--	--	--	--	37.15	--
Total N Load	--	--	--	--	--	--	**96.41**	--
System N Attenuation [b]							**46%**	

a - Stations sampled by Coastal Systems Program, SMAST on 11 sampling dates during warmer months
b - Attenuation calculated between Watershed N Load and Station CC-5.
Note: Nitrogen loads measured within the stream/creek reflect the balance between uptake and new inputs from the watershed.

Table 9. Tidal import/export of nitrogen and chlorophyll a pigments collected near Cockle Cove Creek inlet to Bucks Creek, over a complete tidal cycle on August 3, 2005. Values are total mass flux (kg/tide phase). There was a net export from the Cockle Cove Marshes and associated watershed to Bucks Creek. Sampling was from low tide to low tide (with balance of the salt mass), location is shown in Figure 5. Comparison of the measured net export of nitrogen from the marsh and the nitrogen input from the watershed, from the MEP watershed model (updated April 2006), indicates significant summer attenuation of the nitrogen, 44%.

	NOx	NH_4	PON	DON	BioActive N	Total N	Chl a
Tide Phase							
FLOOD	0.015	0.034	0.870	0.989	0.920	1.698	0.048
EBB	0.233	0.432	1.254	1.917	1.919	3.836	0.047
Ebb-Flood							
Net Export	0.218	0.398	0.384	0.928	1.001	2.138	-0.001
Watershed Land-Use Model N Loading							
Total N Load, per 2 tidal cycles	--	--	--	--	--	**8.60**[c]	--
System N Attenuation [b]						**50%**	

a - Stations sampled by Coastal Systems Program, SMAST on 11 sampling dates during warmer months
b - Attenuation calculated between Watershed N Load and Station CC-5.
c - the daily watershed N loading was adjusted to 2 tidal cycles to compare with the measured tidal flux data.
Note: Nitrogen loads measured within the stream/creek reflect the balance between uptake and new inputs from the watershed.

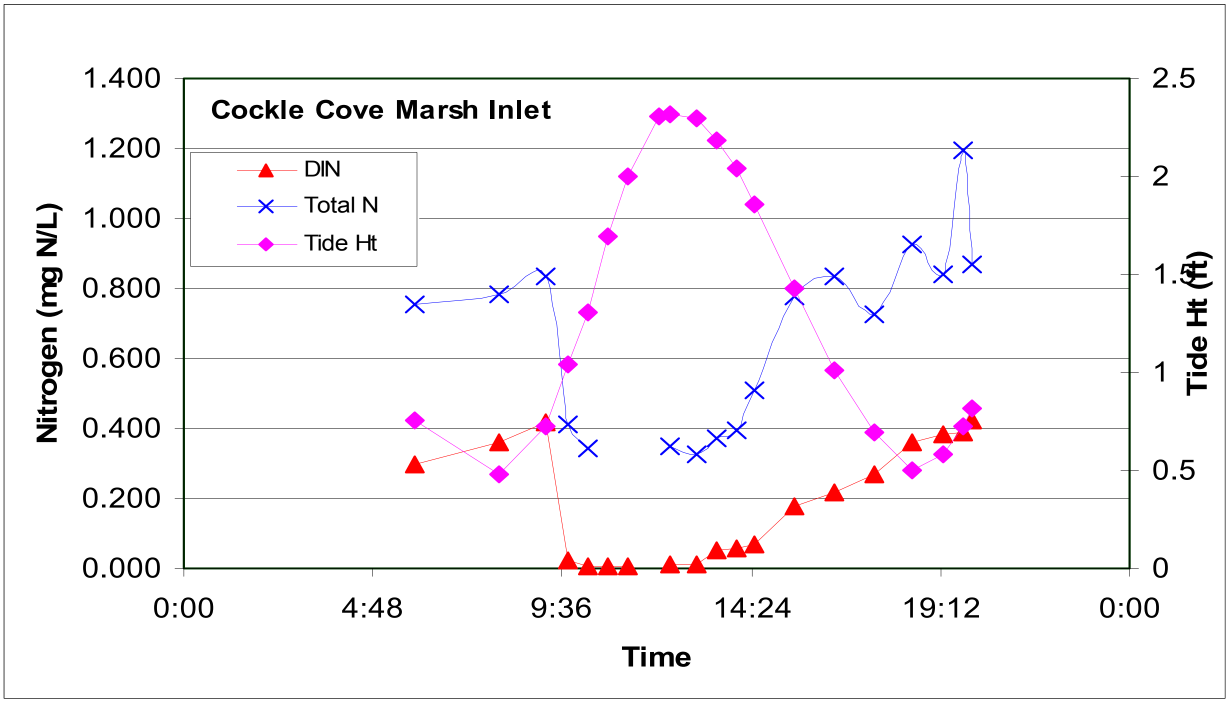


Figure 7. Tide height and concentrations of dissolved inorganic nitrogen (nitrate+ammonium) and total nitrogen over a tidal cycle (8/3/05) near the inlet to Cockle Cove Creek from Bucks Creek (cf. CC-5, Figure 6). The measurements were during a small tide event (~2 ft range) to provide for maximum interaction with tidal channels and minium dilution of watershed nitrogen input by inflowing tidal waters.

C. Stable Isotope Analysis $\delta^{15}N$

Introduction

The use of the naturally occurring stable isotope of Nitrogen (^{15}N**)** to quantify the effect of wastewater effluent on estuarine food webs is becoming widespread. In particular, changes in the naturally occurring ratios of $^{15}N/^{14}N$ in groundwater N due to land disposal of wastewater effluent can have significant impacts on the same ratio in N in marsh creeks as well as marsh flora and fauna, thus creating a wastewater "imprint" in these systems. Typically, studies have shown that groundwater-borne nitrate derived from wastewater has a higher $^{15}N/^{14}N$ ratio (called $\delta\ ^{15}N$) than naturally occurring nitrate. This difference comes from selective denitrification of the lighter (^{14}N) isotope-containing nitrate in the wastewater, leaving a higher proportion of the heavier isotope in the source nitrate. This "fractionation" of the isotopes creates a $\delta\ ^{15}N$ that is higher than that in naturally occurring nitrate. When the $\delta\ ^{15}N$ signal is tracked through the marsh ecosystem, it provides a marker for the presence of wastewater-derived N in the system. This aspect of the Cockle Creek salt marsh assessment was undertaken both to set a baseline for potential future monitoring and to assess the relationship of wastewater nitrogen sources versus other nitrogen sources on key primary producers within the salt marsh system.

Methods
Samples of creek water, macroalgae and marsh grasses were collected from the Cockle Cove Marsh system and analyzed for $\delta\ ^{15}N$ in NO_3 (Creek water) and in the organic matter in the macroalgae, marsh grasses and in suspended particulate matter from the creeks. Assays to determine $\delta\ ^{15}N$ were prepared and carried out in a Mass Spectrometer at SMAST. $\delta\ ^{15}N$ values are given as either + or – relative to the $\delta\ ^{15}N$ of N_2 gas. Reported values are accurate to within 0.1 per mil ($^0/_{00}$).

Results
Nitrate+Nitrite - In the Cockle Cove marsh system, water samples were collected during mid to late ebb tide by SMAST and the Town of Chatham from the creeks at a variety of sites downstream from the wastewater treatment plant. Sites ranged from freshwater sites north of the salt marsh to a site at the mouth of the main channel which merges with the Buck's Creek system (Figure 8). Additional samples were collected from Buck's Creek and the main outlet to Nantucket Sound. Filtered samples (0.22 μ) were analyzed for $\delta^{15}N$ in the NO_3. Results confirm the presence of wastewater derived NO_3 in the creek waters of Cockle Cove Marsh. $\delta\ ^{15}N$ values vary between +7.25 to +14.56 per mil ($^0/_{00}$) (Table 10). Literature values of $\delta\ ^{15}N$ values in wastewater effluent entering groundwater typically range from +10 to +20 $^0/_{00}$ (Kreitler et al. 1978, Kreitler and Browning 1983, Aravena et al. 1993, Macko and Ostrom 1994). In contrast $\delta\ ^{15}N$ values in NO_3 from natural sources range from -1.5 to +8 $^0/_{00}$ (Macko and Ostrom 1994, McClelland and Valiela 1998). Seven of the 13 $\delta\ ^{15}N$ values recorded for NO_3 in creek waters are at or greater than +8 $^0/_{00}$ and 3 are greater than +10 $^0/_{00}$. The remaining 6 samples had $\delta\ ^{15}N$ values ranging from +7.25 to +7.78 $^0/_{00}$. In contrast the $\delta\ ^{15}N$ of water at the inlet to Nantucket Sound is +0.66 $^0/_{00}$ indicating a different source of nitrate in the offshore waters. Note that this sample was collected to represent the boundary condition, inflowing waters from the Sound to Cockle Cove Creek.

There is no notable longitudinal trend of $\delta\ ^{15}N$ values in the NO_3 from the freshwater sites north of the marsh out to the mouth of the creek to Bucks Creek (Figure 8). Values in the freshwater stream north of the marsh range from +7.37 to +12.12 $^0/_{00}$, while those at the mouth and in Buck's Creek range from +7.61 to +14.56 $^0/_{00}$. These data suggest that nitrate removal by the marsh sediments may be uptake by microflora and subsequent coupled nitrification-denitrification may also be important in this system, as was observed in Mashapaquit Creek. In addition, although there is limited data, there is some evidence of direct denitrification (nitrate --> dinitrogen gas), as well.

Macroalgae - Macroalgae were collected at several sites within the marsh, within creeks, along creek banks and from the marsh surface (Figure 9). Results of δ

^{15}N analysis show values ranging from +5.8 to +12.5 $^0/_{00}$ for algae collected from the creeks and creek banks (Table 11) and from +1.0 to +18.3 $^0/_{00}$ for algae collected from the marsh surface (Table 12). Although N uptake by macroalgae results in fractionation of the isotopes (preferential assimilation of ^{14}N over ^{15}N) the $\delta^{15}N$ in the algae generally increases with that of the dissolved inorganic N in the ground water (McClelland and Valiela 1998). The $\delta^{15}N$ values found in the macroalgae from Cockle Cove Marsh are generally in agreement with $\delta^{15}N$ values found in the NO_3 in the creek waters. Algae collected from the marsh surface at CCM 12 near the bridge and at CCM 1 adjacent to the west parking lot recorded $\delta^{15}N$ values of +1.0 and +2.6 $^0/_{00}$ respectively. These values indicate that the algae were probably deposited here from off shore during a flooding tide.

Suspended Particulate Matter - Samples of suspended particulate matter (SPM) were collected near the mouth of Cockle Cove Creek during a tidal cycle, August 3, 2005. The results show that $\delta^{15}N$ values increase from +5.86 to +6.10 $^0/_{00}$ during the late stages of tidal ebb, and then decrease to +4.04 $^0/_{00}$ during tidal flooding, increasing again to +5.26 $^0/_{00}$ prior to the turn of the tide (Figure 11, Table13).

Marsh Grasses - Marsh grasses were collected from 3 sites in Cockle Cove Marsh (Figure 10). At each site, a transect was made from the high marsh through the low marsh to the creek bank. A sample of the grasses in each of these zones was taken and analyzed for $\delta^{15}N$. Results (Table 14) show that $\delta^{15}N$ values at Site 1 adjacent to the west parking lot (Figure 10) range from +2.7 $^0/_{00}$ in grasses from the high and low marsh to +6.0 $^0/_{00}$ in the creek bank. At Site 2 where the marsh creek divides, $\delta^{15}N$ values range from +6.2 $^0/_{00}$ in the low marsh to +7.3 $^0/_{00}$ in the creek bank (data were not available from the high marsh). At Site 3 located in the northern most area of the marsh, $\delta^{15}N$ values ranged from +1.6 $^0/_{00}$ in the high marsh to +0.7 $^0/_{00}$ in the low marsh, to +6.1 $^0/_{00}$ in the creek bank area. In each transect, the highest $\delta^{15}N$ value was recorded in the grasses taken from the creek bank area. $\delta^{15}N$ values are generally lower in high and low marsh grasses, except for low marsh grasses at Site 2 (Table 14). However, it is not possible to determine if the higher creek bank values result from fractionation by denitrification within the sediments or an input of tidally derived nitrogen. In general, emergent plants derive almost their entire nitrogen requirement from nitrogen fixation and recycling and almost none from tidal sources.

Figure 8. $\delta\ ^{15}N$ values of Nitrate with locations and dates where water samples were collected in Cockle Cove Creek.

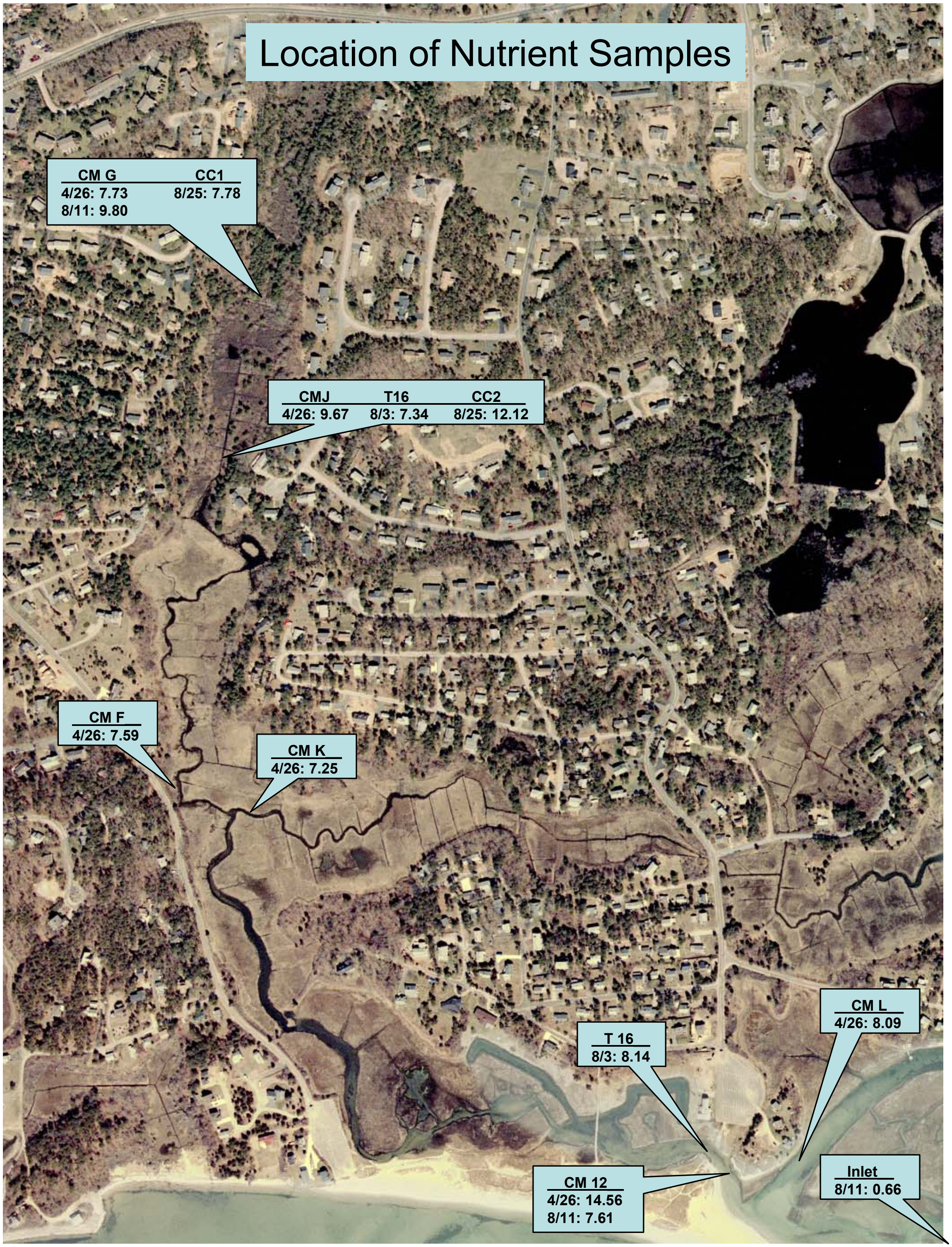


Figure 9. δ^{15}N values of Macroalgae and locations where samples were collected in the Cockle Cove Creek Marsh.

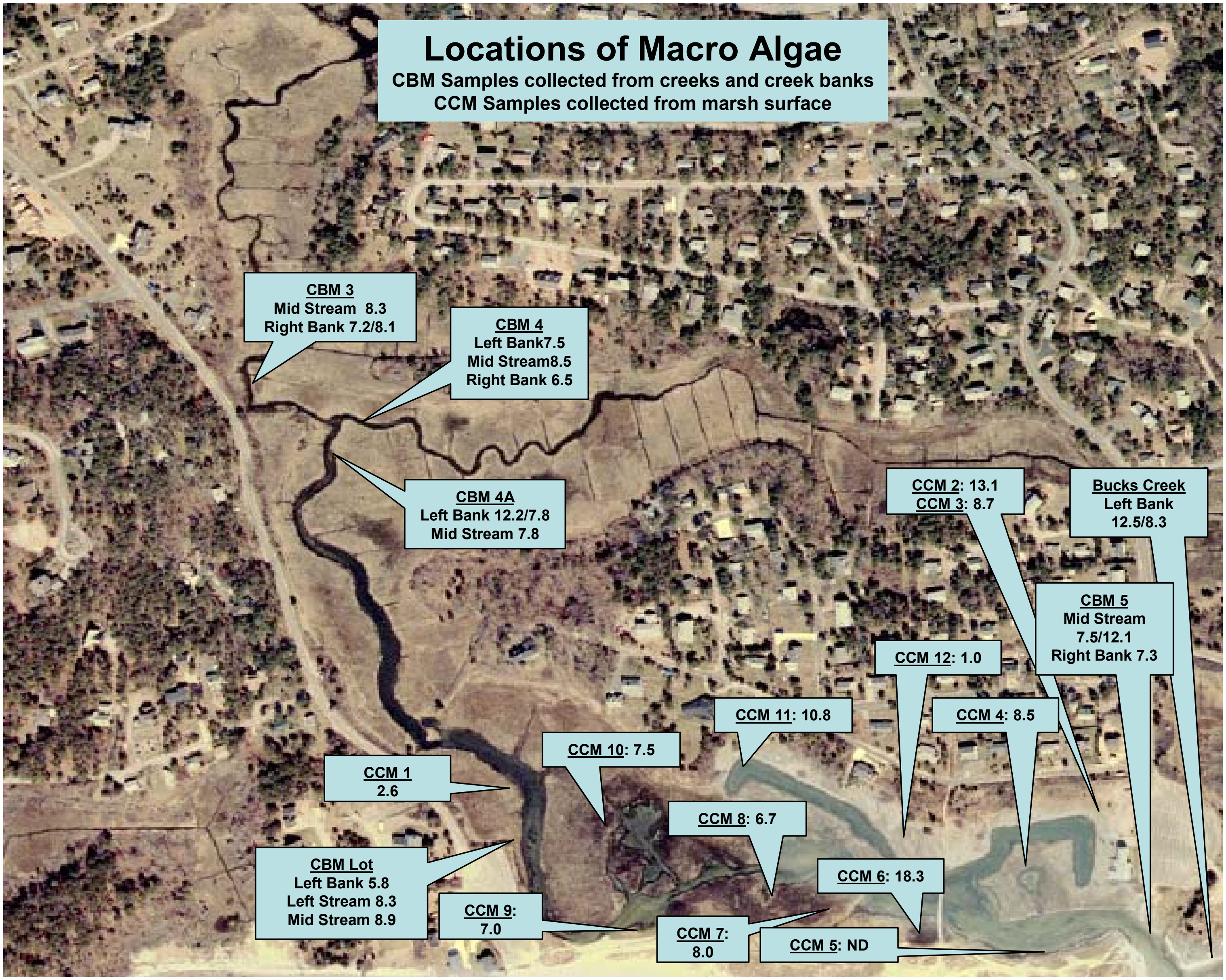
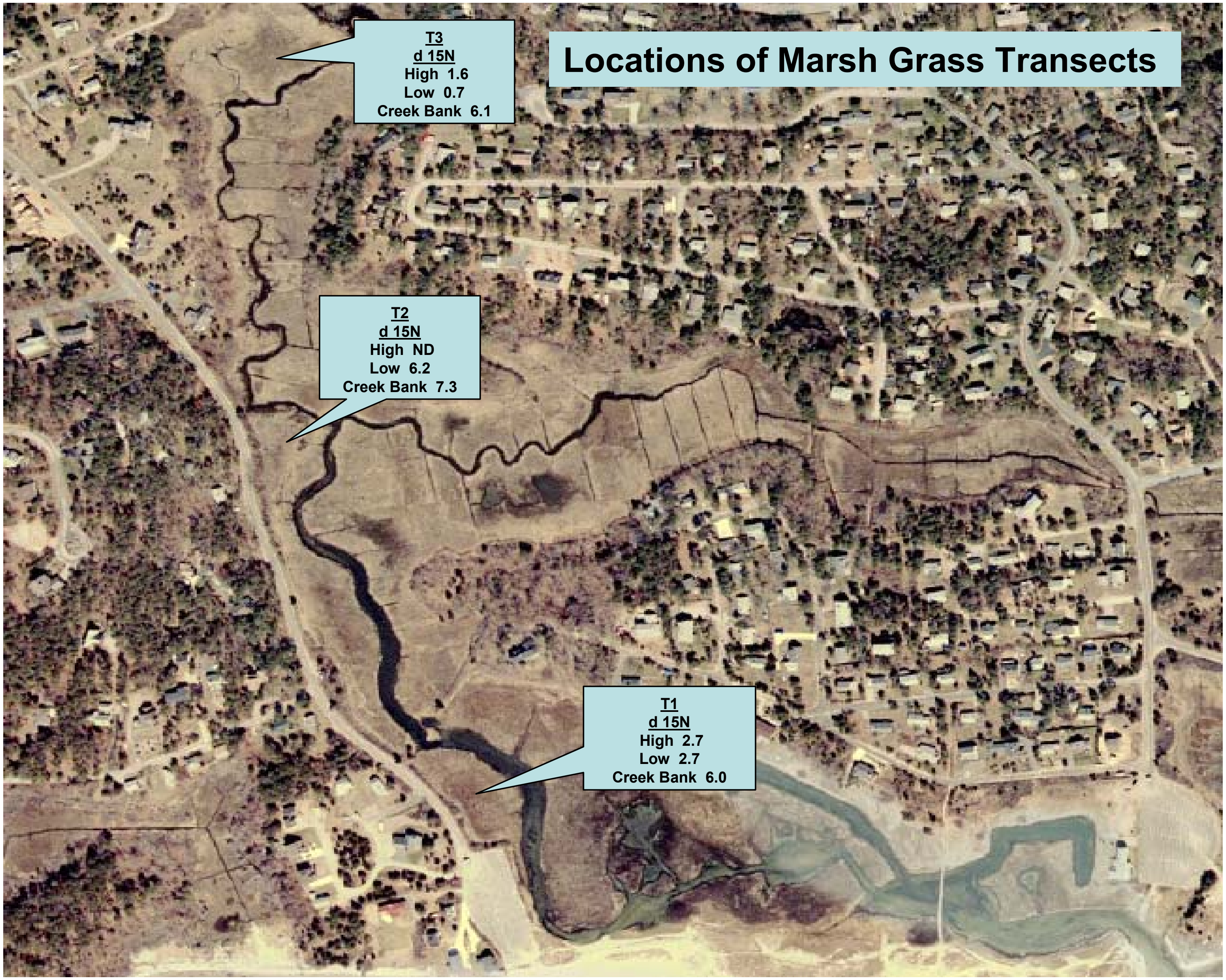


Figure 10. $\delta^{15}N$ values of marsh grasses and locations where samples were collected in the Cockle Cove Creek Marsh.



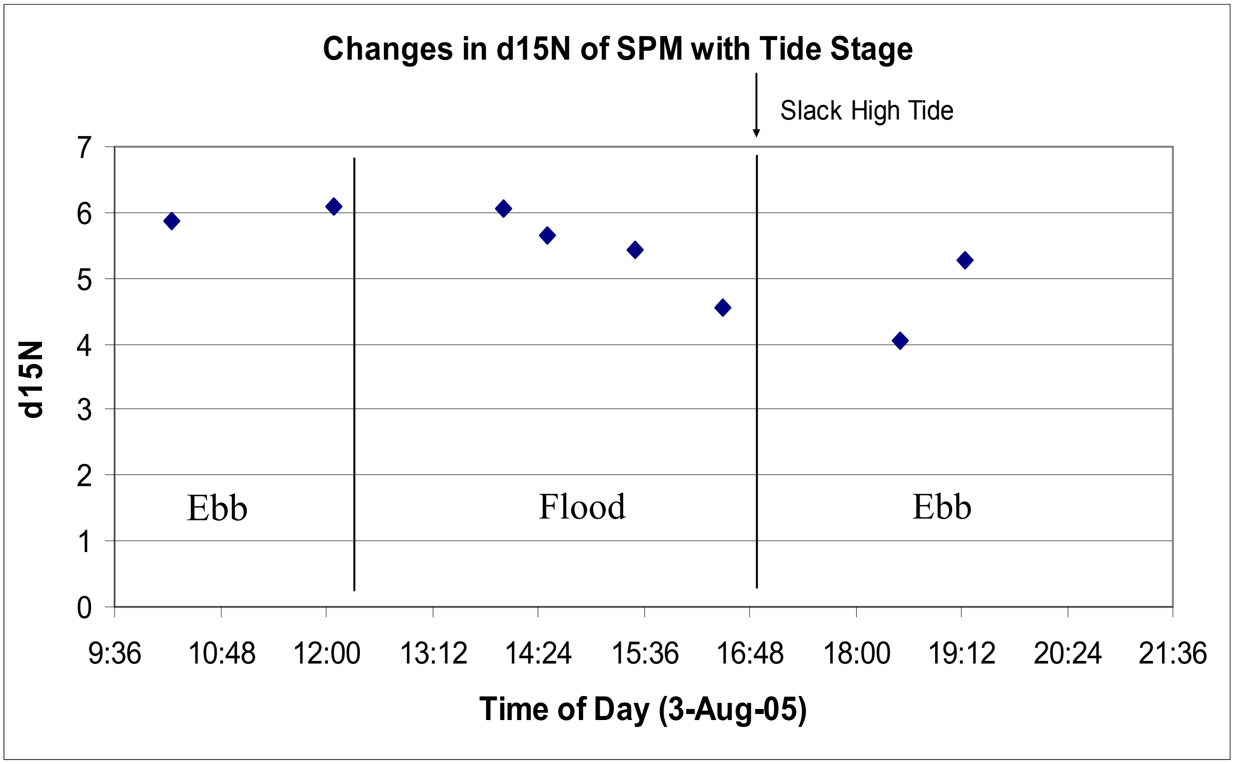


Figure 11. Changes in 15N/14N ratio of particulate organic matter during the tidal flux study, August 3, 2005. The trend of higher ratios at low tide and lower ratios at high tide results from the dilution of wastewater enriched nitrogen within the tidal creek by inflowing offshore waters.

Table 10. δ^{15}N values of Nitrate and locations and dates where water samples were collected in Cockle Cove Creek.

Sample ID	Date Collected	Location	d15N
CM 12	4/26/2005	Mouth	14.56
CM F	4/26/2005	West Fork	7.59
CM G	4/26/2005	FW upstream of Dike	7.73
CM J	4/26/2005	FW Dike	9.67
CM K	4/26/2005	East Fork	7.25
CM 12	8/11/2005	Mouth	7.61
CM G	8/11/2005	FW upstream of Dike	9.80
CM K	8/11/2005	East Fork	11.78
CC 1	8/25/2005	FW upstream of Dike	7.78
CC 2	8/25/2005	FW Dike	12.12
T16 FW	8/3/2005	FW Dike	7.34
T16	8/3/2005	Bridge by Parking Lot	8.14
CM L	4/26/2005	Bucks Creek	8.09
Chatham	8/11/2005	Inlet	0.66

Table 11. δ^{15}N values of Macroalgae collected from the creek and creekbanks in Cockle Cove Marsh

Sample ID	Date Collected	Location	d15N
CC3-A-1	10/6/2005	Right Bank	7.2
CC3-A-2	10/6/2005	Right Bank	8.1
CC3-B	10/6/2005	Mid Stream	8.3
CC4-A	10/6/2005	Mid Stream	8.5
CC4-B	10/6/2005	Right Bank	6.5
CC4-C	10/6/2005	Left Bank	7.5
CC4A-A	10/6/2005	Left Bank	12.2
CC4A-B	10/6/2005	Mid Stream	7.8
CC4A-C	10/6/2005	Left Bank	7.8
CC5-A	10/6/2005	Mid Stream	7.5
CC5-B	10/6/2005	Mid Stream	12.1
CC5-C	10/6/2005	Right Bank	7.3
CC lot-A	10/6/2005	Mid Stream	8.9
CC lot-B	10/6/2005	Left Stream	8.3
CC lot-C	10/6/2005	Left Bank	5.8
Bucks CRK-A	10/6/2005	Left Bank	12.5
Bucks CRK-B	10/6/2005	Left Bank	8.3

Table 12. $\delta^{15}N$ values of Macroalgae collected from the marsh surface in Cockle Cove Marsh

Sample ID	Date Collected	d15N
CCM-1	10/6/2005	2.6
CCM-2	10/6/2005	13.1
CCM-3	10/6/2005	8.7
CCM-4	10/6/2005	8.5
CCM-6	10/6/2005	18.3
CCM-7	10/6/2005	8.0
CCM-8	10/6/2005	6.7
CCM-9	10/6/2005	7.0
CCM-10	10/6/2005	7.5
CCM-11	10/6/2005	10.8
CCM-12	10/6/2005	1.0

Table 13. $\delta^{15}N$ values of Suspended Particulate Matter collected from near the mouth of the creek during a single tidal cycle in Cockle Cove Marsh (3-August-05).

Time Point	Time	Tide Phase	d15N
T4	10:15	Flood	5.86
T7	12:05	Flood	6.10
T11	14:00	Ebb	6.07
T12	14:30	Ebb	5.64
T13	15:30	Ebb	5.44
T14	16:30	Ebb	4.54
T16	18:30	Ebb	4.04
T17	19:15	Ebb	5.26

Table 14. $\delta^{15}N$ values of marsh grasses collected from transects at 3 sites in Cockle Cove Marsh

Transect	Zone	Sample ID	Date Collected	d15N
1	High Marsh	CCM-1A	10/6/2005	2.7
1	Low Marsh	CCM-1B	10/6/2005	2.7
1	Creek Bank	CCM-1C	10/6/2005	6.0
2	High Marsh	CCM-2A	10/6/2005	ND
2	Low Marsh	CCM-2B	10/6/2005	6.2
2	Creek Bank	CCM-2C	10/6/2005	7.3
3	High Marsh	CCM-3A	10/6/2005	1.6
3	Low Marsh	CCM-3B	10/6/2005	0.7
3	Creek Bank	CCM-3C	10/6/2005	6.1

III. Nitrogen Management Threshold

During the MEP analysis of the Cockle Cove Creek sub-system within the Bucks Creek System, it became clear that Cockle Cove Creek was operating as a salt marsh system not an embayment system (e.g. the down-gradient Bucks Creek sub-system for which a threshold was developed). Therefore, it was not possible given the embayment related data to develop a site-specific threshold for this wetland system at that time. However, based upon qualitative observations of the wetland vegetation and creek banks and the absence of observable drift macroalgal accumulations, it appeared that the Cockle Cove Creek marshes were productive and "healthy" under present N loading rates.

Based on previous MEP analysis, a reduction in the present N load was not supported, nor was it possible to set the level of potential increase in N load that would not degrade the habitat quality. It was stated at the time (May 2003, and again in 2004[1]), that additional data would be required to set a wetland specific N loading threshold for this sub-system. Based upon requests (August 2004) from the Town of Chatham to DEP following the TMDL development, the MEP developed a list of salt marsh assessment data that would be required to (1) quantify the present habitat health of the Cockle Cove Creek marshes (Section I), (2) determine the degree of N attenuation within the system (Section II) and (3) provide marsh ecological data needed to support comparisons to other salt marsh systems where quantitative N loading and marsh response data is available (Section III). Therefore, the threshold in this section is based upon the Cockle Cove Creek site-specific data and data from similar marsh types.

The final approach used to develop the nitrogen threshold evolved during the assessment and analysis phase of the project. The initial approach was to conduct a literature survey in an attempt to find salt marsh experimental studies where similar nitrogen thresholds had been developed. No dose/response studies of salt marsh creek bottom communities were found, nor were investigations found quantifying macroalgal accumulation versus nitrogen levels in tidal creeks that would be relevant to the present effort. The general reason for this stems from the general focus on the stimulatory effects on marsh biota of nitrogen, rather than the potential for further eutrophication of these highly productive organic matter rich ecosystems.

The next approach was to develop the information for a comparative analysis across a variety of salt marshes with various nitrogen levels. This analysis required both mining of existing nutrient data and in some cases conducting field observations and discussions with field scientists to gauge ecosystem response (e.g. macroalgal accumulations). The results of this effort in combination with the field assessment data discussed in the prior sections indicated that Cockle Cove waters were highly nitrogen enriched, but that the system was not impaired. These results then fed into an analysis oriented to the mechanism of this nitrogen tolerance and a functional approach to setting a defensible nitrogen threshold. Although it was not possible to set the absolute upper limit, it was possible to determine an allowable nitrogen threshold that should be workable from a wastewater planning perspective.

The MEP thresholds development follows the general approach used for embayments, with adjustment for the unique ecology and biogeochemistry of salt marshes. Unlike embayments, salt marshes are highly tolerant of watershed nitrogen loading. The primary factors supporting this nitrogen tolerance in the emergent vegetated marsh zones stem from (1) the emergent marsh plain is intertidal and dominated by grasses with biophysical mechanisms for dealing with anoxic sediments and high dissolved sulfide levels, (2) the major macroinvertebrates species are adapted to the highly organic sediments and are generally tolerant of periodic hypoxia and sulfide, (3) the creek bottoms are the primary receptor of watershed nitrogen with little entering the emergent marsh zones. The creek bottoms are tolerant of watershed nitrogen loading because they are (1) naturally organic matter enriched receiving large amounts of plant detritus from the creek banks and emergent marsh areas and (2) nearly completely flushed each tidal cycle which limits the potential for phytoplankton blooms. The major discernable shift in habitat quality of the creek bottom environment under enhanced nitrogen loading relates to the accumulation of macroalgae. These macroalgae are generally unattached (due to the unconsolidated substrate) and can result in dense accumulations. Macroalgae in dense accumulations are recognized as causing negative impacts on underlying infaunal communities. In addition, in some circumstances these algae may accumulate on the creek bank grasses possibly causing stress to these emergent plant communities. Therefore, a critical threshold parameter for salt marshes relates to the level of nitrogen where significant macroalgal accumulations occur. As was noted in Section I, above, these accumulations are not observed in the Cockle Cove Creek salt marsh and the emergent vegetated marsh, creek bank and creek bottom habitats appear to be healthy and productive, based upon detailed survey and assessment data. However, as noted in Section II, the tidal creek has high concentrations of inorganic nitrogen and phosphorus.

The present effort to develop the N threshold concentration for the Cockle Cove Creek salt marsh also required comparative data on other healthy and nutrient impaired salt marsh systems. Data synthesized from these comparative salt marshes included (1) dominant vegetation type, (2) tide range, (3) the ebb tide nitrogen (4) configuration (central creek versus basin or pond) and (5) macroalgal species and general abundance.

Twenty three salt marsh areas were identified and the data compiled by the Technical Team. The focus was on macroalgal accumulations or other clear indicators of nitrogen over-loading. However, as put forward previously, the analysis focused on Cockle Cove Creek and its salt marsh function, not the downgradient sub-embayments of Bucks Creek/Sulphur Springs. Therefore, the nitrogen threshold developed herein relates only to the Cockle Cove Creek salt marsh, the sub-embayment nitrogen threshold remains unchanged.

The nitrogen threshold for the salt marsh is based upon several observations presented in the sections above:

- The emergent vegetated marsh is healthy and productive.
- The creek bank vegetation and macroinvertebrates are indicative of a healthy productive New England salt marsh.
- Macroalgae indicative of nitrogen enrichment (*Ulva*, filamentous greens) were sparse along the creek banks.
- The creek bottom infaunal community was diverse and productive and indicative of a healthy salt marsh creek.
- Macroalgae indicative of nitrogen enrichment (*Ulva*, filamentous greens) were sparse within the creek bottoms, and the drift algae in the lower marsh reach was sparse and appeared to be entering on the flood tide.
- The marsh creek waters on ebb tide held high levels of inorganic nitrogen and phosphorus relative to that needed to promote algal growth.

The high levels of nitrogen and phosphorus, yet the absence of macroalgae, suggests that physical factors may be playing a key role in habitat quality in this tidal creek system. The most obvious physical factor is the high degree of flushing in this salt marsh compared to other marshes with ponds or basins which allow nutrient enrichment and the accumulation of drift algae (through lowered tidal velocities). The MEP Technical Team assessed tidal velocities using the numerical hydrodynamic model and found that Cockle Cove Creek has relatively high velocities of 1.1 ft sec^{-1}, which compares well with Little Namskaket Creek (1.13 ft sec^{-1}), another similarly configured marsh that drains at low tide and does not support macroalgae even under nitrogen enrichment. However, comparing Cockle Cove Creek to Mashapaquit Marsh (or Aucoot Cove salt marsh), which is nitrogen enriched and has significant macroalgal accumulations revealed much lower velocities (0.44 ft sec^{-1}). The velocity data relates to the inability of drift algae to accumulate if there are no basins or low velocity areas to allow settling. This is the case in Cockle Cove Creek. In fact, the only area where drift algae was observed was in the dredged lagoons near the tidal inlet.

In addition, the inter-marsh comparison indicated that the systems with macroalgal accumulations (Table 15) had <u>both</u> high nitrogen levels and low velocity areas (Aucoot Cove, Mashapaquit Creek, Warrens Cove, mouth of Peconic River). Systems with moderate macroalgal accumulations also appear to have low velocity areas (Agawam River and Duck Creek). The Agawam River is a deep tidal river with a residence time many fold longer than Cockle Cove Creek. The most striking observation from Table 15 is that high nitrogen levels alone do not result in macroalgal accumulation. Rather, the data support the contention that a low velocity area is needed for the macroalgae to accumulate. It also appears that the watershed nutrients not removed by the Cockle Cove salt marsh are exported to Bucks Creek and then to Nantucket Sound. Increasing the nitrogen load to Cockle Cove Creek will increase the nitrogen transport to these downgradient systems, but as long as the nitrogen levels and specifically the bioactive nitrogen levels (nitrate+ammonium+PON) do not increase, there is no evidence that there will be a discernable change in the quality of the various habitats within this salt marsh.

The principal point to be made is that as long as the concentration of bioactive nitrogen (nitrate+ammonium+PON) in the tidal creek remains unchanged, the habitats should remain of high quality. A key parameter in the salt marsh creek is that the creek water can not accumulate nutrients over multiple tidal cycles as is the case in embayments. In addition, increasing the nitrogen concentration in the tidal waters that flood the marsh plain will have a negligible or possibly a stimulatory effect on marsh primary and likely secondary production (i.e. an enhancement of habitat). Since the inflowing fresh waters flow down gradient through the marsh creek and out to the Sound, the nitrogen level will never exceed the inflowing freshwater nitrogen level of 2.960 mg N L^{-1} or 3.154 mg N L^{-1} of bioactive and total nitrogen respectively (Stations CM-J and CC 2, Table 7). Since there was not a sampling station between the freshwater entry point and mid salt marsh (1.687 and 1.921 mg N L-1 for bioactive N and TN), it can only be noted that the upper marsh is exposed to nitrogen levels between these values. However, the upper salt marsh also shows no discernable impairment. It is important to note that since the creek bottom sediments are removing nitrogen, the concentration of out-flowing water will decline along the tidal reach. It appears then that as long as the tidal creek maintains its present hydrodynamics, an entering bioactive N level of 3.0 mg N l-1 would be protective or a total N level of 2.5 (mean of fresh inflow and mid-marsh concentration) within the upper salt marsh reach.

If a highly conservative value was desired then a total nitrogen level of 2.0 mg N L-1 throughout the salt marsh should be employed since the marsh creek reach between the stream and mid-marsh experiences levels between 3.1 mg TN/L and 2.0 mg TN/L. This can be accurately translated to a nitrogen concentration in the discharge from the WWTF using the USGS groundwater model, however, it would appear that an WWTF upgrade to tertiary treatment would result in treated effluent level (3.0 or 2.5 mg DIN L^{-1}), below that required to be protective of Cockle Cove Creek. The environmental concern over increased discharge volume would focus upon the amount of freshwater from effluent relative to the total freshwater inflow to the salt marsh and more significantly the effect on down gradient waters of Bucks Creek/Sulphur Springs and near shore Cockle Cove if the total N load were to increase over present conditions. However, the data all support the conclusion that increasing the present nitrogen load to the headwaters of Cockle Cove Creek will not negatively impact the salt marsh system as long as the nitrogen concentration is maintained and the system maintains its present flushing and velocity characteristics. This should allow for a several fold future increase in flow from the WWTF, should it be needed to support the Town's nitrogen management program.

Table 15. Comparison of nitrogen related water quality parameters and algal abundance in Salt Marshes throughout S.E. Massachusetts (Peconic Bay on Long Island is also included). The marshes are divided into "creek" marshes which have a main tidal creek typical of New England salt marshes which drains out at low tide and "pond" or "basin" marshes, which have a relatively deep basin which retains water at low tide. Observed algal types are primarily algal mat attached to the sediment surface or unattached macroalgae, usually *Ulva*. Data are from various research studies by the Coastal Systems Program, SMAST over the past 25 yrs and from NERR database for Stage Lot Pond. Cockle Cove Creek data was collected by the Town of Chatham Water Quality Laboratory and the Chatham Water Quality Monitoring Program and by SMAST staff.

Salt Marsh	WWTF Y/N	Creek Basin	Depth (m)	Salinity (ppt)	Chl a (ug/L)	Water Concentration (uM) NOx	NH4	PON	DON	DIN	BioAct N	TN	PO4	Macroalgae Type	Density	Impact?
Cockle Cove Salt Marsh																
upper/mid	**Y**	**Creek**	**0.3**	**4.4**	**--**	**85.8**	**22.9**	**11.8**	**16.7**	**108.7**	**120.5**	**137.2**	**1.7**	Drift	Sparse	None
mid	**Y**	**Creek**	**0.3**	**6.7**	**--**	**62.5**	**22.4**	**15.0**	**18.5**	**84.9**	**99.9**	**118.4**	**2.2**	Drift	Sparse	None
Hall Creek Marsh	N	Creek	1.30	29.7	4.8	0.5	1.6	9.1	31.5	2.2	11.3	42.8	0.4	Drift	Sparse	None
Great Sippewisset M	N	Creek	0.5	30.0	3.0	1.0	2.0	3.5	24.4	3.0	6.5	30.9	0.5	filament	Sparse	None
Little Sippewisset M.	N	Creek	0.67	29.9	5.0	0.7	1.2	10.1	22.1	1.8	11.9	34.0	0.4	filament	Sparse	None
Ellisville Marsh	N	Creek	1.51	28.1	31.0	0.8	2.7	25.0	24.1	3.6	28.6	48.8	0.7	None	Low	Low
Back River	N	Creek	1.58	28.2	0.7	1.2	1.3	11.4	17.6	2.5	13.9	31.5	0.7	Algal Mat	Low	None
Little Namskaket M.	N	Creek	0.87	22.9	6.4	8.0	8.9	14.6	46.4	16.9	31.5	78.3	2.1	Algal Mat	Low	Low
Centerville R.-Upper	N	Creek	0.93	21.2	9.5	3.5	5.8	17.8	26.6	9.3	27.1	53.6	0.6	Algal Mat	Mod	Low
Namskaket Marsh	N	Creek	3.42	24.9	7.3	4.0	6.6	15.4	30.1	10.2	25.6	56.1	1.3	Ulva	Sparse	Low
Rock Harbor Marsh	N	Creek	1.12	20.6	8.9	5.5	8.3	16.5	45.2	13.7	30.2	75.4	1.4	Ulva	Sparse	Low
Aucoot Marsh, Inlet	Y	Creek	0.99	29.4	4.3	1.6	2.3	7.7	21.7	3.9	11.7	33.5	1.5	Ulva	Mod/Low	Low
Duck Creek, Wellflee	N	Creek	3.23	30.8	7.2	0.7	6.6	14.9	44.0	7.3	22.2	66.3	1.4	Ulva	Low	Mod/Low
Agawam River	Y	Creek	0.60	6.9	27.9	5.6	18.2	26.1	25.1	23.8	49.9	75.2	1.2	Ulva	Mod	Mod
Wankinco River	Y	Creek	3.08	22.1	9.6	1.3	4.8	11.4	25.2	6.1	17.5	43.3	1.2	Ulva	High	Mod
Aucoot Marsh-mid	Y	Creek	0.40	27.9	8.9	5.4	6.9	14.0	39.5	12.3	26.3	65.8	4.7	Ulva	High	Mod
Mashapaquit Creek	Y	Creek	0.36	18.8	32.7	19.1	1.1	25.3	19.4	20.2	45.6	65.0	0.3	Ulva	High	High
Sage Lot Pond	N	Pond		29.9	9.1	0.6	1.8	11.1	16.9	3.7	14.8	37.2	1.5	None	Low	Low
Eel Pond	N	Basin	0.90	27.2	0.7	1.4	1.6	8.9	18.5	2.9	11.8	30.2	0.7	Algal Mat	Low	None
Bumps River	N	Basin	1.05	23.9	5.7	4.5	3.3	12.5	26.8	7.7	20.2	47.0	0.3	Algal Mat	High	Mod/Low
Ellisville Marsh	N	Pond	0.58	27.4	16.0	1.1	2.6	15.4	21.4	3.9	19.3	38.9	0.7	Ulva	Sparse	Low
Peconic River Head	Y	Basin	1	25.0	10.0	0.8	2.6	24.9	26.6	3.4	28.3	54.9	0.5	Ulva	High	High/Mod
Warren Cove Marsh	N	Basin	1.35	23.5	11.3	1.4	2.3	16.7	25.4	3.7	20.4	45.9	0.6	Ulva	High	High

Background Literature

Overview of New England Salt Marshes and Nitrogen

Teal, J.M. 1986. The Ecology of Regularly Flooded Salt Marshes of New England. Community Profile from Fish and Wildlife (Dept of Interior) Biological Report 85(7.4).

Kennish, M.J. 1986. Ecology of Esuaries. Vol I. Physical and Chemical Aspects. CRC Press, pp. 254.

Nixon, S.W. 1980. Between coastal marshes and coastal waters – a review of twenty years of speculation and research on the role of salt marhses in estuarine productivity and water chemistry, p. 437-525. In: P. Hamilton and K. Macdonald (eds). Estuarine and Wetland Proceses with Emphasis on Modeling. Plenum Press, New York.

Nixon, S.W. 1982. The ecology of New England high salt marshes: a community profile. U.S. Fish and Wildlife Service Division Biological Service, Wahington, D.C. FWS/OBS-81/55.

Denitrification in salt marshes – relevant to this region (these are regional studies, more complete list of references within)

Review Articles:

Koike, I. and J. Sorensen. 1988. Nitrate Reduction and Denitrification in Marine Sediments. In: Nitrogen Cycling in Coastal Marine Environments, p. 251-273.. H. Blackburn and J. Sorensen (eds), SCOPE, John Wiley & Sons.

Salt Marsh Publications:

Abd. Aziz, B and D. Nedwell. 1986. The nitrogen cycle of an East Coast, U.K. saltmarsh: II. Nitrogen fixation, nitrification, denitrification, tidal exchange. Estuarine Coastal Shelf Science 22:689-704.

Howes, B.L., P.K. Weiskel, D.D. Goehringer and J.M. Teal. 1996. Interception of freshwater and nitrogen transport from uplands to coastal waters: the role of saltmarshes. pp. 287-310, In: "Estuarine Shores: Hydrological, Geomorphological and Ecological Interactions (K. Nordstrom and C. Roman, Eds.). Wiley Interscience, Sussex, England.

Hamersley, M.R. and B.L. Howes. 2005. Coupled nitrification-denitrification measured in situ in a Spartina alterniflora with a $^{15}NH_4^+$ tracer. Marine Ecology Progress Series 299:123-135.

Kaplan, W., I. Valiela and J. Teal. 1979. Denitrification in a salt marsh ecosystem. Limnology and Oceanography 24:726-734.

Valiela, I. and J. Teal 1979. The nitrogen budget of a slat marsh ecosystem. Nature 280:652-656.

Nitrogen and Salt Marsh Plants – relevant to this region
(these are regional studies, more complete list of references within)

Hamersley, M.R. and B.L. Howes. 2005. Coupled nitrification-denitrification measured in situ in a Spartina alterniflora with a 15NH4+ tracer. Marine Ecology Progress Series 299:123-135.

Howes, B.L., J.W.H. Dacey and D.D. Goehringer. 1986. Factors controlling the growth form of *Spartina alterniflora*: feedback between above-ground production, sediment oxidation, nitrogen and salinity. J. Ecol. 74:881-898.

White, D.S. and B.L. Howes. 1994 Translocation, remineralization and annual turnover of nitrogen in the roots and rhizomes of Spartina alterniflora. American Journal of Botany 81: 485-495.

White, D.S. and B.L. Howes. 1994. Long-term 15N-nitrogen retention in the vegetated sediments of a New England salt marsh. Limnology and Oceanography 39: 1878-1892.

Whiting, G., H. McKellar, J. Spurrier and T. Wolaver. 1989. Nitrogen exchange between a portion of vegetated salt marsh and the adjoining creek. Limnology and Oceanography 34:463-473.

Wolaver, T, J. Zieman, R. Wetzel and K. Webb. 1983. Tidal exchange of nirogen and phosphorus between a mesohaline vegetated marsh and the surrounding estuary in the lower Chesapeake Bay. Estuarine Coastal Shelf Science 16:321-332.

Valiela, I., J. Teal and N. Persson. 1976. Production and dynamics of experimentally enriched salt marsh vegetation: Belowground biomass. Limnology and Oceanography 21:245-252.

Sources of data for Table 15 – Intermarsh comparison.

Barnstable (Town) and Three Bays Preservation Water Quality Monitoring Programs, Personnal Communication.

Coalition for Buzzards Bay Monitoring Program. Personal Communication.

CDM and Howes, B.L. 2000. Water Quality Evaluation of the Wareham River Estuary Complex. Final Report to the Town of Wareham. Camp, Dresser and McKee Inc. 300pp.

DEP/SMAST Massachusetts Estuaries Project Nutrient Technical Reports (Centerville River; Three Bays; Back River).

DeSimone, L, B. Howes, D. Goehringer and P. Weiskel. Wetland Plants and Algae in a coastal marsh, Orleans, Cape Cod, Massachusetts. U.S. Geological Survey Water-Resources Investigations Report 98-4011, pp33.

Ellisville Marsh Water Quality Monitoring Project & ACRE/SMAST Restoration Study.

Howes, B., Schlezinger, N. Millham, G. Hampson, and D. Goehringer. 1997. Oxygen uptake and nutrient regeneration in the Peconic Esuary. Final Report to the Suffolk County Department of Health Services, 68 pp.

Orleans (Town) Water Quality Monitoring Program.

Smith, K. 1999. Salt marsh uptake of watershed nitrate. Master's Thesis. Department of Geology, Graduate School of Arts and Sciences, Boston University, Boston Massachusetts. 76 pp.

Valiela, I. and J. Teal 1979. The nitrogen budget of a slat marsh ecosystem. Nature 280:652-656.

Weiskel, P.K., L.A. DeSimone and B.L. Howes. A nitrogen-rich septage-effluent plume in a coastal aquifer, marsh and creek system, Orleans, Massachusetts: project summary, 1988-1995, U.S. Geological Survey Open-File Report 96-11, 20p.

WHOI 1993. Water quality monitring of Aucoot Cove, MA. Reprot to the U.S. EPA – Buzzards Bay Project.

Appendix A.

Cockle Cove Plant and Invertebrate Surveys

August 2005

Coastal Zone Management
Investigative Report