Draft/Final Report

Nutrients, Eutrophication and Harmful Algal Blooms in Buzzards Bay, Massachusetts

SFY'99 Interdepartmental Service Agreement (ISA) between the Massachusetts Department of Environmental Protection (DEP) and the University of Massachusetts Dartmouth

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Executive Summary

Since October, 1987, Professor Jefferson Turner and his students and Research Associates from the University of Massachusetts Dartmouth have conducted 141 cruises monitoring environmental parameters in Buzzards Bay to establish temporal and spatial trends of hydrography, water quality and plankton community structure. This program has been funded by the Massachusetts Department of Environmental Protection (DEP) under its Research and Demonstration (R & D) Program. This monitoring has quantified temperature, salinity, water clarity, inorganic nutrients (ammonium, nitrate + nitrite, phosphate, silicate) chlorophyll a + phaeopigments, and bacterioplankton abundance on monthly cruises at eight stations throughout the bay. Samples have also been collected and preserved for quantitative taxonomic analyses of abundance and community composition of phytoplankton, zooplankton, and ichthyoplankton. Additional parameters measured at some but not all stations, or for part but not all of the sampling period include dissolved oxygen, primary productivity (photosynthetic rates) and age and growth of larval fish. From October, 1987 – October, 1998, there was a monitoring cruise every calendar month, year-round, with no interruptions.

This report summarizes eleven years (1987-1998) of hydrographic, nutrient, chlorophyll, bacterioplankton, and water clarity data for all eight stations, as well as quantitative taxonomic data for 372 phytoplankton samples collected from 1988-1998 at three stations along a gradient from the middle of the bay, to the New Bedford sewage outfall, to the inner harbor of New Bedford. The goal of these studies was to ascertain whether fluctuations in nutrient and water quality parameters could relate to recurrent blooms of toxic or otherwise harmful phytoplankton blooms, that could result in shellfish toxicity. Observations from the single year of our phytoplankton community composition data completed thus far (1987-88) revealed that there was a bloom of the toxic dinoflagellate *Alexandrium tamarense* in New Bedford Harbor in summer of 1988. Also, many areas historically closed to shellfishing due to sewage pollution are now in the process of being opened, due to conversion of New Bedford's sewage treatment facilities from primary to secondary treatment in September, 1996. Thus, there is the real possibility that sewage remediation may increase vulnerability to shellfish toxicity caused by harmful phytoplankton.

Buzzards Bay exhibits large seasonal and interannual variations in levels of certain parameters. These were particularly apparent for nitrate, silicate and phytoplankton abundance and composition. Other parameters showed more uniform distributions, with the exception of the two stations in New Bedford Harbor. Distributions of phosphate and chlorophyll *a* had concentrations that were generally similar bay-wide on a given day, and over seasons and years for the six stations away from New Bedford Harbor. However, the signals for elevated concentrations of ammonium, phosphate, and chlorophyll *a* at the sewage outfall, were apparent. High concentrations of these parameters would be expected to reflect sewage effluent, and these data clearly identify the New Bedford sewage outfall as the major eutrophication insult to Buzzards Bay prior to conversion to secondary treatment. However, the increased water transparency and decreased levels of ammonium, bacterioplankton, rod-shaped bacteria after conversion to secondary treatment clearly indicate improved water quality at the sewage outfall.

Phytoplankton abundances recorded here ($0.012 - 26.0 \times 10^6$ cells l^{-1} for Cruises 18-141, 1988-1998) are higher than generally reported from previous studies in other coastal waters of New England. The reason is that our preservation of samples with Utermohl's solution did not destroy the delicate microflagellates and phytoflagellates which so completely dominated phytoplankton abundance. Most other studies of phytoplankton abundance in New England coastal waters have used formalin as a preservative, thus destroying the microflagellates, and biasing records in favor of diatoms and thecate dinoflagellates which survive formalin preservation.

The bay-wide patterns for silicate suggest the possibility of biological control of silicate levels due to variations in silicate utilization by phytoplankton. Since diatoms are the dominant phytoplankters utilizing silicate, and summer dominance by non-silicate-utilizing microflagellates and dinoflagellates is a common pattern in estuaries of the northeastern United States, the possibility is raised that summer silicate increases in Buzzards Bay were due to differential utilization of silicate due to changes in phytoplankton community composition.

Phytoplankton community analyses suggest that silicate levels generally decline from early to mid-summer highs in response to a late summer phytoplankton blooms. These blooms are typically composed of diatoms. Thus, the typical late-spring to early-summer spikes in silicate levels frequently coincided with the seasonal zenith in dominance by microflagellates and dinoflagellates, and annual nadir in diatom dominance. These patterns are apparent when comparing silicate levels and percentage of the

phytoplankton comprised by diatoms, where periods of diatom dominance are seen to occur at low levels of silicate, and vice versa. Potentially-harmful algal species recurrently recorded (at low abundances) for Buzzards Bay include diatoms of the genus *Pseudo-nitzschia*, and the dinoflagellate *Alexandrium tamarense*. Both taxa have been associated with shellfish toxicity, and their continued presence in Buzzards bay suggests a need for continued phytoplankton monitoring.

In conclusion, Buzzards Bay appears to be a favorable habitat for phytoplankton in that it is well-mixed and -illuminated, and nutrient-replete. Although there were obvious eutrophication signals from the New Bedford sewage outfall prior to secondary treatment, in terms of high ammonium and chlorophyll *a*, and low light penetration, the rest of the estuary appears relatively unimpacted. Hydrography, bacterioplankton abundance, nutrients and phytoplankton pigments were highly variable in time and space. While most locations away from New Bedford Harbor exhibited similar values on a given day, the stations at the sewage outfall and inner harbor usually had much higher values than the rest of the bay. There were also major fluctuations in nutrients and phytoplankton pigments on time scales ranging from biweekly to monthly to seasonal to interannual. Although much of this fluctuation appeared due to physical forcing, some such as silicate appears to be biologically-driven. Consideration of parameter variability in Buzzards Bay is essential for proper understanding and management of this system.

Introduction

Estuaries are variable habitats. Their water masses and populations exhibit natural fluctuations on time scales ranging from tidal cycle to daily to seasonal to interannual. Superimposed over this natural variability are anthropogenic influences that can change both temporally and spatially. This is particularly true for estuaries that are partially urbanized. Attempts to manage such systems can be hampered by lack of baseline ecological data, and inability to separate natural from human-induced variability. It is often difficult to recognize "abnormal" because we do not appreciate the variability that is "normal". Buzzards Bay, Massachusetts (Fig. 1) is such an estuary.

Until recently, information on the ecology of Buzzards Bay has been surprisingly limited. This is despite the fact that studies in the bay date back almost a century (Peck 1896, Sumner et al. 1913, Fish 1925, Lillick 1937). There have been major studies of benthic communities (Sanders 1958, 1960, Wieser 1960, Rhoads & Young 1970, Young 1971, Rhoads et al. 1975), as well as examination of the effects of tidal resuspension on the water column (Roman & Tenore 1978, Roman 1978, 1980). However, other studies of pelagic communities of Buzzards Bay are limited. Aside from two months of samples for phytoplankton at a single station in Buzzards Bay (Lillick 1937), and Anraku's (1964) survey of adult copepods in relation to the Cape Cod Canal, the plankton and most other aspects of the water-column ecology of Buzzards Bay have been virtually unstudied. Recent publications on plankton have been specialized, dealing with meroplankton only (Butman 1989) or benthic resting eggs of a single species of planktonic copepod (Marcus 1984, Marcus & Fuller 1989). It seems that the water column of Buzzards Bay has historically been viewed from the benthos up rather than from the surface down.

There has been a recent resurgence of interest in Buzzards Bay, partly due to concerns about pollution. Sediments in New Bedford Harbor contain large amounts and complex mixtures of toxic compounds (Pruell et al. 1990), long-term effects of an oil spill are still apparent (Sanders et al 1980), and "cultural eutrophication" of Buzzards Bay embayments is proceeding (Valiela & Costa 1988). Buzzards Bay has been classified by NOAA/EPA (1989) as high in susceptibility to concentrating particulate and dissolved pollutants due to large overall estuarine volume relative to comparatively low volume of freshwater inflow that would flush the estuary. Although bay-wide nitrogen loading is relatively low, specific sites such as the New Bedford sewage outfall exhibit substantial eutrophication effects (Smayda, 1989). Although information on specific, usually polluted, subsections of the bay continues to accumulate in reports to regulatory agencies and student theses, information on such basic parameters as inorganic nutrient distributions has lacked sufficient temporal and spatial coverage to quantify trends (Stenner et al. 1988), particularly for the open waters of the bay.

Nutrient loading and eutrophication of coastal marine waters is increasingly becoming a problem at many locations around the globe. Anthropogenic nutrient enrichment from sewage disposal or agricultural runoff can stimulate overproduction of phytoplankton biomass, which upon decomposition can cause reduced water quality or anoxia. Also, nutrient enrichment may be linked to a possible epidemic of toxic or noxious phytoplankton blooms (Smayda 1990).

Like other urbanized estuaries, Buzzards Bay has portions that are becomming increasingly eutrophic. A conspicuous area is New Bedford Harbor, where the city's sewage outfall discharged >90,000 m^{-3} d^{-1} of poorly-treated effluent that was, until 1996, nominally primary treated, but in actuality appeared and smelled to be virtually untreated. However, the bay is large (590 km^2), and many areas receive little anthropogenic discharge or natural runoff. Also, due to shallow depths (<20m) and dynamic wind and tidal mixing, resuspension of bottom sediments frequently injects regenerated nutrients from the benthos back into the water column (Rhoads et al. 1975, Roman 1978). Thus, the nutrient regime of Buzzards Bay is complicated, and it is important to clarify temporal and spatial patterns throughout the estuary.

Beginning in October, 1987, Professor Jefferson Turner and his students and Research Associates from the University of Massachusetts Dartmouth (UMD) started monitoring environmental parameters in Buzzards Bay to establish temporal and spatial trends of hydrography, water quality and plankton community structure. This program has been funded by the Massachusetts Department of Environmental Protection (DEP) under its Research and Demonstration (R & D) Program. This monitoring has quantified temperature, salinity, water clarity, inorganic nutrients (ammonium, nitrate + nitrite, phosphate, silicate) chlorophyll a + phaeopigments, and bacterioplankton abundance on monthly cruises at eight stations throughout the bay (Figure 1). Samples have also been collected and preserved for quantitative taxonomic

analyses of abundance and community composition of phytoplankton, zooplankton, and ichthyoplankton. Additional parameters measured at some but not all stations, or for part but not all of the sampling period include dissolved oxygen, primary productivity (photosynthetic rates) and age and growth of larval fish. From October, 1987 – October, 1998, there was a monitoring cruise every calendar month, year-round, with no interruptions (see Table 1).

The work force in this program has been primarily undergraduate and graduate students, with obvious apprenticeship value. Thus far several dozen undergraduate, and over a dozen graduate students have participated in cruises and/or laboratory analyses of data, and several students have performed M. S. thesis research from this project.

Products resulting from this study, other than the aforementioned Master's theses (Borkman, 1994; Pierce, 1992; Chute, 1995; Gauthier, 1997; Hill, 1998), include a progress report summarizing the first year of the project (Turner et al. 1989), a report summarizing the first three years of the project (Turner et al. 1994), seven published papers in peer-reviewed journals or symposia (Turner & Borkman, 1993; Borkman & Turner, 1993; Borkman et al. 1993; Turner et al. 1995; Pierce & Turner 1994a; 1994b; Nakamura & Turner, 1997), and other manuscripts either submitted (Chute & Turner, 1999) or in preparation (Turner, Lima, & Pierce, 1999; Hill, Turner, Hobbie, & Tucker, 1999).

This project is now becoming one of the longest-running environmental time series for coastal waters anywhere in the world that measures as many parameters as we do. Although the value of such long-term data sets is widely appreciated, few exist. Our study will undoubtedly bring positive recognition to our Buzzards Bay monitoring program, UMD, and the Massachusetts DEP and the Executive Office of Environmental Affairs (EOEA) in national and international arenas.

Although funding for continuation of monitoring in Buzzards Bay was inexplicably discontinued by the DEP in 1998, funding was provided by the Massachusetts EOEA through the DEP and for maximizing information gained from completion of analyses of archived samples and data already collected. In particular, was completion of quantitative taxonomic analyses of selected phytoplankton samples collected but not analyzed for over a decade of monitoring, and consolidation of nutrient and other water quality data that may relate to changes in phytoplankton communities. The goal of these studies was to ascertain whether fluctuations in nutrient and water quality parameters could relate to recurrent blooms of toxic or otherwise harmful phytoplankton blooms, that could result in shellfish toxicity. Observations from the single year of our phytoplankton community composition data completed thus far (1987-88) revealed that there was a bloom of the toxic dinoflagellate *Alexandrium tamarense* in New Bedford Harbor in summer of 1988. Also, many areas historically closed to shellfishing due to sewage pollution are now in the process of being opened, due to conversion of New Bedford's sewage treatment facilities from primary to secondary treatment in September, 1996. Thus, there is the real possibility that sewage remediation may increase vulnerability to shellfish toxicity caused by harmful phytoplankton. An expanded rationale for the present study is presented below.

Rationale

Why is it important to record fluctuations and/or changes in phytoplankton community composition? There are several reasons. Various phytoplankton taxa respond differentially to such parameters as light, temperature, and concentrations of various nutrients, as these driving parameters change with season, interannually, and/or in response to anthropogenic manipulation. The phytoplankton community responds with changes in relative and/or absolute abundance of various taxa. As water quality deteriorates, certain "nuisance" taxa would be expected to flourish. Conversely, if water quality improves, and indications near the New Bedford sewage outfall indicate that it has, then the phytoplankton community would be expected to also reflect such changes.

There have been numerous suggestions of a global increase in blooms of toxic or otherwise harmful phytoplankton species, and that these may relate to anthropogenic changes in coastal waters (Anderson, 1989; Smayda, 1989; 1990; Hallegraeff, 1993). In particular, it appears that changes in nutrient ratios may favor increased blooms of various types of harmful algae. For instance, if levels of silicate become limiting, but levels of nitrogen and phosphorus remain sufficient, there may be a shift from silicate-requiring diatoms to non-silicate-requiring taxa such as dinoflagellates or microflagellates. As ratios of N:P decline due to phosphate loading from domestic or agricultural runoff, there may be a shift from chlorophytes to nitrogen-fixing cyanobacteria. Conversely, if N:P ratios increase in response to nitrogen loading from sewage, there may be a shift toward dominance by high-nitrogen-requiring chlorophytes.

Understanding of such interactions is usually hampered by absence of background data on nutrient levels, nutrient ratios, and particularly phytoplankton community composition.

Along with 11 years (1987-1998) of monthly nutrient data from Buzzards Bay, we have taken concurrently-collected phytoplankton samples, but these were analyzed for community composition only for 1987-88 (Borkman, 1994; Pierce, 1992; Pierce & Turner, 1994a; Borkman et al. 1993; Turner et al. 1995). Thus, the present study was designed to maximize information needed to understand phytoplankton:nutrient interactions in Buzzards Bay, whereby selected archived phytoplankton samples were analyzed for community composition and abundance. The reason that this had not been done already was lack of funds for trained personnel to perform the extremely laborious and time-consuming microscopic analyses of phytoplankton samples. The only analyses (1987-88) prior to the present study came from M.S. thesis research projects.

Several important observations have already resulted from our 1987-88 phytoplankton analyses. It appears that dinoflagellates bloom regularly over the annual cycle in Buzzards Bay. Such blooms usually follow diatom blooms that have stripped the water of silicate, but have left concentrations of nitrogen and phosphorus sufficient to support blooms of dinoflagellates or other algae which do not require silicate (Borkman et al. 1993). Thus, the typical "spring bloom" can actually be "spring blooms" of first diatoms, and later dinoflagellates or other non-silicate-requiring species.

We also appear to have made the first recording of a bloom of *Alexandrium tamarense* (formerly *Gonyaulax tamarensis*) in Buzzards Bay (Pierce & Turner, 1994a; Turner et al. 1995). Although this dinoflagellate is well-known for causing red tides and shellfish toxicity in coastal waters of New England (Anderson, 1997), surprisingly it had never been recorded to bloom in Buzzards Bay. However, the most likely reason for this was that there had been no sampling for phytoplankton abundance and community composition in Buzzards Bay prior to the onset of the UMD monitoring program in 1987. Pierce & Turner (1994a) and Turner et al. (1995) reported that *A. tamarense* was a regular component of the phytoplankton of Buzzards Bay from June to October, 1988. Although it was found at all stations, it was more typical of the northern area and the Cape Cod Canal. Typical abundances were low, in the range of 10 - 100 cells/liter, but in July, 1988 it bloomed in the inner harbor of New Bedford at levels of 3,000 cells/liter. It is not known if this bloom produced shellfish toxicity since New Bedford Harbor has been closed to shellfishing for nearly a century due to sewage contamination. However, with improving water quality in New Bedford Harbor due to sewage remediation, there has been recent limited opening of the outer harbor to shellfishing since conversion from primary to secondary treatment. If *Alexandrium tamarense* is a regular summer component of the phytoplankton in New Bedford Harbor and Buzzards Bay, then opening of additional areas to shellfishing should be coupled with increased monitoring of both water and shellfish for PSP toxins.

Contractual Obligations

There are several primary aspects to these studies, listed in the Scope of Services. These include three major tasks:

"1. Document any changes in phytoplankton commnity abundance and composition coincident with fluctuations in recorded levels of inorganic nutrients.

2. Focus upon phytoplankton and nutrient changes in response to conversion of the New Bedford wastewater treatment facility from primary to secondary treatment in September, 1996 (between Cruises 116 and 117), which by indications from several other parameters (ammonium, water clarity, bacterioplankton abundance) has greatly improved water quality at the outfall station.

3. Expand upon observations from phytoplankton community data completed thus far (1987-88) that there may be re-occurring red tide blooms of the toxic dinoflagellate *Alexandrium tamarense* in New Bedford Harbor that could cause paralytic shellfish poisoning if and when this area is opened to shellfishing."

The present draft/final report responds to "Tasks 7B and 7C: Project Administration and Reporting. Deliverable 7A, Quarterly Reports and invoices" listed in the Scope of Services. Status on various aspects of the project, and data completed, are presented by task.

Task 1: Perform Quantitative Phytoplankton Analyses.

A major aspect to our proposed studies is quantitative taxonomic analyses of phytoplankton community composition from selected archived samples. Since we have performed over 140 cruises with 8 stations per cruise, and 3 depths per station (surface, mid-depth, and bottom), we have over 3,000 archived phytoplankton samples. However, we did not need to analyze all of them, for several reasons. Comparisons presented in Borkman (1994) revealed, for the 1987-88 samples (Cruises 1 – 17), that since the water column in Buzzards Bay is routinely isothermal, there are few vertical discontinuities in phytoplankton abundance or community composition. Thus, by analyzing surface samples only, we can get virtually all of the information that might be obtained by the much more laborious analyses of all samples. Further, even though 8 stations were analyzed per cruise (see Fig. 1), Borkman (1994) revealed that the major gradient of change of phytoplankton abundance and composition was along a line from inner New Bedford Harbor (Station 8), to the New Bedford sewage outfall in the outer harbor (Station 7), to the middle of Buzzards Bay (Station 6). Thus, by analyzing surface samples from each of these 3 stations, we could generally characterize the phytoplankton of Buzzards Bay by analyzing 36 samples per year. For the ten years between October, 1988 (when Borkman's 1994 analyses ended) and September, 1998 (the end of our funded period of sampling), that would be only 372 samples (for Cruises 18-141).

Phytoplankton analyses have been completed. They were done by Jean Lincoln, a part-time Research Associate with considerable experience in phytoplankton analyses. She has been performing phytoplankton analyses in Turner's laboratory, on various projects, since 1992. She completed her M.S. degree under Turner's direction in 1998, and since graduation has been working identifying phytoplankton on this and another project at the UMD Center for Marine Science and Technology (CMAST).

Task 2: Completion of analyses and reduction of nutrient, chlorophyll and other water quality data.

This aspect of the project is also completed. All frozen nutrient and chlorophyll samples have been analyzed, and data reduction has been completed. Analyses and reduction of nutrient data was done by two part-time Research Associates, David Borkman and David Gauthier. Both are former graduate students of Turner, and both have been heavily involved in collection and analyses of nutrient data for this project. Similarly, all chlorophyll, dissolved oxygen, salinity, water clarity and bacterioplankton samples have been analyzed, and graduate students John Kieser and Carrie Dunn have been heavily involved in calculating final values for these parameters from raw data, and transferring these data from handwritten data books to computer spreadsheets. These students have also contributed greatly to organization and computerization of nutrient and phytoplankton species data.

All nutrient, chlorophyll, hydrographic, light and bacterioplankton data for the eleven years of the project (Cruises 1-141) are presented in tabular format in appendix tables in this report. All phytoplankton data from Cruises 18-141 are provided as an appendix to this report. Phytoplankton data for cruises 1-17 are presented in Borkman (1994).

Tasks 3 – 7 (presentations and reports):

Presentations of data, either in reports or in person obviously obviously had to await completion of data analysis, reduction, graphic presentation, and interpretation, as described above. We have completed all data analyses and reporting by the June 30, 1999 deadline for the end of the project. However, since the formal initiation of this project was inexplicably delayed by the DEP for five (5) months until an official start date of December 1, 1998, we assume that there can also be some slippage in the schedule for public presentations of results, as presently described in the scope of services. When we proposed to do analyses of a decade of phytoplankton samples, it was with the expectation that it would be a twelve (12) month project, not a seven (7) month one. Due to Jean Lincoln beginning phytoplankton analyses prior to December 1, 1998, and working on them for approximately two (2) months prior to being paid to do them, she was able to finish analyses of the phytoplankton samples by early June (just barely). Thus, even though we had originally planned to perform these analyses in twelve (12) months, and have been funded to do so

over a period of seven (7) months), Jean Lincoln was able to actually complete them in nine (9) months, the seven for which she is being paid, as well as the approximately two months prior to start date, when she was not.

Our team instituted a "crash program" in April through June, 1999 to finish up the draft/final report by the end of June, once all phytoplankton analyses were completed. Any subsequent modifications to the written report and public presentations will soon follow, although they will occur after July 1, 1999. We have discussed with Mr. Arthur Screpetis of the DEP the possibility of an extension of the period for funds ($5,000.00) for preparation of public presentations, and preparation of pamphlets, posters, reports, and other "hard-copy" materials for a few months past the June 30, 1999 deadline.

Methods

Stations

Samples were collected at 8 stations throughout Buzzards Bay (Fig. 1). Three of these (Stations 4, 5, & 6) were at buoys along the central axis of the bay at depths of 10-15 m. Station 2 (depth = 8-12 m) was at the southwestern end of the Cape Cod Canal. At this station there are strong tidal currents (up to 4 knots) which change direction every 6 h. In order to complete sampling of the entire bay in one day, all stations were sampled upon arrival irrespective of the state of the tide. Stations 1 and 3 were in the shallow embayments of Mattapoisett and Megansett Harbors at depths of 5-8 m. Station 7 (depth = 6-8 m) was over the subsurface outfall of the primary treatment sewage plant of New Bedford. Station 8 (depth = 8 m) was in the main channel of the inner harbor of New Bedford. This harbor is almost completely enclosed by a stone hurricane dike, thus circulation is restricted relative to the rest of the bay (Signell 1987, Geyer & Dragos 1990). All stations were precisely located by Loran or GPS coordinates. Water column depths at a given station varied with tidal range, which in Buzzards Bay ranges from approximately 1.0-1.5 m.

Sampling

Samples were collected at all 8 stations on each of 141 cruises between 1 October 1987 and 11 September 1998 (Table 1). All stations were sampled in a single day on each cruise. Cruises were monthly except for biweekly cruises in October, 1987, June-October, 1988, and June-August, 1989.

At each station temperature was measured to the nearest 0.01°C with a Beckman temperature probe at 1 m intervals over the entire water column. Water transparency was measured with a 30 cm diameter white Secchi disk, with estimates to the nearest half meter. Water samples were collected with Niskin bottles from surface, mid-depth, and near-bottom depths. These samples were used for synoptic salinity, nutrient, chlorophyll *a* and phaeopigment, phytoplankton, (Cruises 1-141) data, and (surface only) bacterioplankton data for Cruises 2 -141, and dissolved oxygen (DO) data from Cruise 56 onward. Salinity was measured (to the nearest $^{o}/_{oo}$) with a refractometer.

Light Penetration

The 1% isolume depth (ie. bottom of the euphotic zone) was calculated from Secchi disk measurements by:

Isolume depth (in meters) - ln (fraction of light)/(-K),
where: fraction of light is percent of that at the surface
(ie. 0.01 for 1%),
and: extinction coefficient (K) = 1.44/Secchi depth (in meters).

Bacterioplankton

Bacterioplankton samples were collected from the surface only, beginning with Cruise 2. Aboard ship 18 ml of surface water was preserved with 2 ml of 12% 0.2 µm-filtered gluteraldehyde solution, for a final concentration of 0.6% gluteraldehyde. Samples were kept refrigerated until epifluorescence microscopic analyses, usually within 1-2 days after each cruise.

Cells were concentrated by filtration of 5 ml subsamples onto 0.2 µm-pore size black Nucleopore filters, and stained with DAPI (Porter & Feig 1980). Filters were sandwiched between coverslips and slides with non-fluorescing immersion oil. Bacterioplankton cells were counted at 1,250 x with oil immersion using a Olympus BH-2 epifluorescence microscope equipped with an ocular Whipple disk. At least 400 cells were counted, giving a counting accuracy of better than $\pm$ 10% (Guillard, 1973). Knowing the

dimensions of each Whipple disk field and the total filtration area containing cells, it was possible to calculate the fraction of the total sample that had been counted.

We did not separate photosynthetic versus non-photosynthetic protists (Caron, 1983), but obtained counts of microflagellates in phase-contrast analyses of phytoplankton samples preserved in Utermohl's solution (Guillard, 1973) that were concentrated by sedimentation rather than filtration.

Nutrients

At surface, mid-depth and bottom depths at all stations on all cruises, concentrations of ammonium, nitrate, nitrite, orthophosphate and silicate were measured (n = 3,384 samples for each nutrient). To avoid measuring levels of nutrients in plankton or other particulates, in addition to dissolved nutrients, all samples were prefiltered aboard ship through Whatman GFC glass fiber filters. Blanks on unfiltered water were performed to correct for any silicon additions from the filters. Samples were refrigerated, but not frozen, until return to the laboratory (< 1 h after docking), and frozen in the laboratory prior to analyses.

Analyses were performed with either a Technicon Autoanalyzer 2 (Cruises #1-17) or a Alpkem RFA-300 Elemental Analyzer (Cruises #16-141). An intercalibration of both instruments on all samples from cruises #16 & 17 revealed comparable data. The chemistry for analyses with both instruments was essentially that of Parsons et al. (1984).

Chlorophyll a and Phaeopigments

Samples from surface, mid-depth and bottom depths at all stations on all cruises (n = 3,384) were filtered aboard ship through Whatman GFC glass fiber filters. Either 100 ml or usually 200 ml was filtered, and filters were coated immediately with 1% $MgCO_3$ to prevent pigment degradation. Filters were individually wrapped in aluminum foil and kept on ice until return to the laboratory. Either the night after each cruise, or the next day (after freezing overnight) filters were disintegrated in 90% acetone and kept for an additional day in a freezer in the dark for maximum extraction of pigments. Chlorophyll *a* and phaeopigment analyses were done with a Turner Designs Model 10 fluorometer according to the methodology of Parsons et al. (1984). Phaeopigment analyses were after acidification with 2 drops of 1 N HCl.

Dissolved Oxygen

Measurements of dissolved oxygen (DO) were initiated at the request of the DEP, beginning with cruise 57 (September 24, 1991), and continuing through Cruise 141. DO measurements were made on samples from surface, mid-depth and bottom depths from Stations 6, 7, and 8, only, using the Winkler titration method (Parsons et al., 1984).

Phytoplankton

Phytoplankton samples were collected at surface, mid-depth and bottom depths with Niskin bottles. Approximately 800 ml of raw seawater from each depth was preserved in Utermohl's iodine solution (Guillard, 1973). This preservative does not cause disintegration of athecate cells such as microflagellates, as does formalin which has been used in most historical phytoplankton studies in coastal waters of the northeastern United States.

Phytoplankton counts were made on samples concentrated by gravimetric sedimentation, usually from approximately 800 ml to a final concentrate of 50 ml. Samples were counted in Sedgwick-Rafter counting chambers. Use of a Olympus BH-2 phase-contrast microscope equipped with long-working-distance objectives < 4 cm in length allowed use of the Sedgwick-Rafter cells at both low and high magnifications, rather than, as usual, only at low magnification.

Phytoplankton analyses were performed on each sample at both high (400 x or 500 x) and low (200 x or 250 x) magnifications. This was to accurately quantify abundances of small cells that might not be seen in routine examinations at the lower magnifications, but to also quantify abundances of larger, albeit rarer cells, that would have been missed by examining only a smaller aliquot, the size of which was dictated by abundance of smaller, more abundant cells. Counts would be made at high magnification until enough grids (measured by a calibrated Whipple Disc in the eyepiece) had been counted to give at least 400

cells, thereby giving a precision of at least ± 10% (Guillard, 1973). Counts were then made on the each sample at low magnification, recording all cells in a 0.5 ml volume, recording all taxa not encountered in the high magnification count. All cells were identified to species, or if species identification was uncertain, to the lowest possible taxon.

Two different phase-contrast compound microscopes were used, one at the main campus of UMass Dartmouth, and the other at the Center for Marine Science and Technology (CMAST). Since the one on main campus had a 1.25 x column magnifier, that meant that magnifications on the 20 x and 40 x objectives (with 10 x oculars) would have actually been 250 x and 500 x, respectively. Since the microscope at CMAST had no 1.25 x column magnifier, then acutal magnifications with 20 x and 40 x objectives (and 10 x oculars) were 200 x and 400 x. These differences in magnification, and their effects on the areas of the grids counted with the two different microscopes, were accounted for in the spreadsheet calculations for phytoplankton.

Phytoplankton analyses were made on 372 samples from Stations 6, 7, and 8 (Fig. 1). In all but a few cases, samples were from surface depths. However, in a few cases, surface samples had dried out during extended storage, so counts for those stations came from mid-depth or bottom samples. These samples included Cruise 18, Station 8 (bottom); Cruise 31, Station 6 (mid-depth), Cruise 37, Station 8 (mid-depth), Cruise 81, Station 6 (mid-depth).

Results

Due to the large amount of data comprising this report, graphic presentations of data are presented in Appendices 1-10. Tables listing data comprise nearly a thousand pages. Thus these tables have been provided to the DEP as Appendices 11-17 of this report, and though they are referenced in the text, they are not attached to other copies of this report.

Summary data (means and ranges) for light penetration, bacterioplankton, dissolved oxygen and chlorophyll *a* and nutrient data are presented in Table 2. Summary data for phytoplankton abundance and percentage composition are presented in Table 3.

Temperature

There was pronounced seasonality of surface temperature (range = -2.0 to 27.3°C) (Fig. 2) during all years of the study (plots by station in Appendix 1, tabular data in Appendix 11). Due to wind and tidal mixing, and shallow depths, the water column was usually isothermal with < 1°C variation between temperatures measured at every meter between the surface and bottom except during summer (May or June through August or September). Although vertical profiles of temperature are not presented here, as shown by Turner & Borkman (1993), using vertical profiles of temperature for summer of 1988, any thermal discontinuity was only near bottom at some stations, and rarely > 4°C cooler than surface temperatures.

Salinity

Salinity (data not shown) was almost uniformly 30 ‰ throughout the study at virtually all times (range = 26 to 31 o/oo). The only times when salinities were low were at Station 8 in the enclosed inner harbor of New Bedford, immediately after or during heavy rain.

Light Penetration

Buzzards Bay is usually visibly green, so Secchi disk values were low (range for all stations = 0.8 – 12.0 m, mean = 3.9 m). However, at Station 7 over the New Bedford sewage outfall, water color was usually brown due to fine particles of sludge. Secchi disk values at this station were 0.8 – 6.0 m, with a mean of only 2.3 m, < 60% that of the rest of the bay. After the New Bedford sewage treatment facility converted from primary-treated effluent to secondary-treatment in September, 1996 (between Cruises 116 and 117), there was a marked increase in Secchi disk values (Fig. 3). Plots of Secchi disk values by station are presented in Appendix 2 and tabular data are presented in Appendix 12.

Despite the generally low Secchi disk values, since Buzzards Bay is shallow, generally < 10 m, most of the water column is in the euphotic zone, with illumination > 1% of surface levels, most of the time (mean of 92.61% of the water column euphotic, range for all stations = 34.29 – 100%). Together with the high nutrient levels, this illuminated water column allows for substantial phytoplankton growth throughout most of the year, explaining the "green" water color, and hence the low Secchi disk values.

Bacterioplankton

Surface bacterioplankton abundance for Cruises 2 – 141 only (no bacterioplankton data were produced for Cruise 1) averaged 2.58 x 10^6 cells ml^{-1}, with a range for all stations of 0.18 – 10.92 x 10^6 cells ml^{-1} (Table 2), with pronounced seasonal fluctuation (plots by station in Appendix 3, and tabular data in Appendix 13). Bacterioplankton abundance was generally higher in summer and lower in winter. Bacterioplankton abundance was generally higher at Station 7 (New Bedford sewage outfall) and Station 8 (New Bedford inner harbor) than elsewhere in the bay.

The bacterioplankton assemblage was almost exclusively comprised of small cocci < 1 μm in diameter, except at the sewage outfall station (Station 7) where rod-shaped cells > 2 μm in length were always abundant (Cruises 2-116), generally comprising means of 30% of cells. However, after the New Bedford sewage treatment facility was converted to secondary treatment (September, 1996, between Cruises 116 and 117), the large rod-shaped bacteria were no longer present. Since these bacteria were presumed to have been fecal coliform bacteria, their disappearance at Station 7 after conversion to secondary treatment indicates improved water quality.

Dissolved Oxygen

Dissolved oxygen (DO) measurements were only initiated beginning with Cruise 57 (September 24, 1991), and only taken at Stations 6, 7, and 8. In some cases DO data were not taken, or samples were lost due to spillage (Cruises 60, 70, 79, 85-87, various depths on Cruises 97, 98, 103, 124 – see table in Appendix 14). DO levels averaged 9.1-9.3 mg l^{-1} (Table 2), and minimum levels (2.0-3.0 mg l^{-1}) were always encountered during the warmer months (plots in Appendix 4). With a very few such exceptions, DO levels were high, as would be expected in the well-mixed, shallow waters of Buzzards Bay.

Chlorophyll a

Surface chlorophyll *a* levels were comparatively high (mean for all stations = 6.19, range = 0.10-64.66 μg l^{-1}) and relatively uniform throughout the bay on a given day except for high summer concentrations at Stations 7 (sewage outfall) and 8 (inner harbor) (plots in Appendix 5, tabular data in Appendix 15). There was no long-term decline in chlorophyll levels, such as that recorded for Narragansett Bay by Li & Smayda (1998).

Nutrients

Nutrient values over all depths are presented in tabular form in Appendix 16, and plots in Appendices 6-9. Due to the shallow holomictic water column, nutrient levels at all stations except Station 7 were generally similar with depth. Thus, plots of temporal distributions by station (Appendices 12-15) present mean values, with error bars denoting ranges between surface, mid-depth and bottom values. Due to the surface plume of effluent from the New Bedford sewage outfall, levels of ammonium and phosphate at the surface at Station 7 were usually higher than at other depths at the same station, or at any depth in the rest of the bay. This was less the case for distributions of nitrate and silicate. Such a pattern would be expected in an area impacted by sewage effluent, since ammonium is a degradation product of urea, and high phosphates in sewage reflect detergents in wastewater (Ryther & Dunstan 1971). High levels of ammonium and phosphate were also found at Station 8 in the New Bedford inner harbor, but levels were generally similar throughout the water column. This probably reflects shallow depth (8 m), runoff from the Acushnet River which empties into the northern end of the harbor, and prolonged residence times of water retained behind the hurricane dike.

Surface ammonium levels were highest at Station 7 with much lower and comparatively uniform levels elsewhere (Appendix 6), and ammonium was the major form of inorganic nitrogen available throughout the bay. As a percentage of total dissolved inorganic nitrogen (D.I.N. = $NH_4^+ + NO_3^- + NO_2^-$), ammonium comprised up to > 99%, with a mean for all stations of 76.08% (Table 2), likely reflecting the shallow water column and resuspension of ammonium regenerated in the benthos. Ammonium values were typically higher during the warmer months, particularly at Station 7. Ammonium levels at the sewage outfall (Station 7) were also somewhat lower after September, 1996 (Cruise 116) when the sewage treatment facility converted to secondary treatment. Peak levels of ammonium after that time never as high as those recorded prior to conversion to secondary treatment (Appendix 6).

Surface distributions of nitrate + nitrite (Appendix 7) were different from those of ammonium. Nitrate fluctuations over time were much more bay-wide than those of ammonium, the latter of which were heavily biased by the sewage outfall. There was also considerable interannual variability in nitrate + nitrite distributions within given months, as well as considerable variability between depths at given stations at the same time (note height of range bars in plots in Appendix 7).

Surface phosphate distributions (Appendix 8) showed clear peaks during the warmer months at Station 7 in most years. Otherwise, phosphate levels were comparatively uniform and low (mean = 1.04, range = 0.00-8.86 μM) throughout the rest of the bay, compared to a mean of 2.58 μM, range = 0.08 – 27.02 μM, at Station 7. The high phosphate levels at Station 7 are likely a reflection of sewage effluent, in that the mean concentration at this station was nearly three times that for the rest of the bay.

There were generally bay-wide summer increases in silicate levels, followed by precipitous declines in fall, during most years (Appendix 9). The regularity of this trend was not matched by any other nutrient, suggesting a unique, possibly biological cause. This suggestion was also supported by the fact that silicate levels at the sewage outfall (Station 7) were not the highest recorded, nor were maximum values at Station 7 particularly higher than elsewhere in the bay.

Phytoplankton

A summary of phytoplankton abundance and percentage composition data is presented in Table 3. Individual station phytoplankton data are plotted in Appendix 10, and tabular presentation of phytoplankton data by station (746 pages) have been provided to the DEP as Appendix 17.

Total phytoplankton abundance at Stations 6, 7, and 8, averaged approximately 3.0 – 5.4 x 10^6 cells l^{-1}, with maximum values of 26 x 10^6 cells l^{-1}. In terms of mean, maximum and minimum phytoplankton abundance, there was a clear progression of increasing phytoplankton abundance from the middle of the bay (Station 6) to the sewage outfall (Station 7) to the inner harbor (Station 8). There were no consistent seasonal trends in abundance of total phytoplankton (plots in Appendix 10). Rather, there was considerable variability in total abundance with season in different years, as well as from station-to-station on a given cruise.

Phytoplankton abundance was overwhelmingly dominated by microflagellates, comprising means of approximately 73-86% of total cells counted (plots in Appendix 10). The designation "microflagellates" was used for spherical cells < 5 μm, and mostly < 2 μm in diameter. The next-most-abundant category of cells was "phytoflagellates," comprising means of 9.7 – 16.5% of total cells. This category included teardrop-shaped cells of the genus *Pyramimonas*, small flagellates of the genus *Calycomonas*, and oval or oblong cryptomonads.

Although scores of diatom taxa were recorded, diatoms comprised means of only 2.9-8.0% of cell abundance (Table 3). However, during certain bloom situations, diatoms occasionally comprised up to 90% of cells at a given station. The main diatom species that exhibited major blooms was *Skeletonema costatum* (plots in Appendix 17), usually in late summer or fall. On occasion, blooms of this species approached 10 – 12 x 10^6 cells l^{-1} at the sewage outfall (Station 7) and in the inner harbor of New Bedford (Station 8). *S. costatum* also forms major blooms in Narragansett Bay which exhibit considerable interannual variability in timing, occurring primarily in winter-spring or summer-fall (Smayda, 1998; Karentz & Smayda, 1984; 1998). Other diatom genera that exhibited blooms, which were highly variable in time and space, included *Rhizosolenia, Chaetoceros*, and *Thalassiosira*. These genera included several species each, which often bloomed in concert.

The primarily diatom taxon which could be considered "harmful" is *Pseudo-nitzschia multiseries*. This species has produced toxic blooms elsewhere in North America with occasional fatal intoxication of

humans or seabirds after ingestion of shellfish of fish containing the neurotoxin domoic acid, produced by this diatom (Bates et al. 1998). Since diatoms of the genus *Pseudo-nitzschia* are potentially of concern in Buzzards Bay, an expanded account of taxonomic problems associated with this genus are presented below.

There are potentially four species of the genus *Pseudo-nitzschia* that could occur in New England coastal waters: *P. pungens, P. multiseries, P. delicatissima*, and *P. pseudodelicatissima*. Although there are reports of all four of these species producing domoic acid, either in field collections, or in culture (see Table 1 of Bates et al. 1998), the primary species that has been associated with domoic acid shellfish toxicity episodes in the North Atlantic is *P. multi-series*. The reports of domoic acid toxicity in the field for *P. pseudodelicatissima* and *P. delicatissima* are based upon only single occurrences, in either the Bay of Fundy or at Prince Edward Island, Canada, respectively. The only published report of domoic acid toxicity in the field attributed to *P. pungens* was from New Zealand, although there have apparently been recent unpublished reports (summarized by Bates et al., 1998) from California and Washington (state). Several other species of the genus, which may or may not produce domoic acid all occur in the Pacific. Based upon criteria given in the Hasle and Syvertsen (1997) chapter of a manual edited by Tomas (1997) entitled "Identifying Marine Phytoplankton," it is possible to distinguish these four species using microscopy, but in some cases, only using scanning electron microscopy (SEM). Criteria are given below.

Members of the genus *Pseudo-nitzschia* form end-to-end chains, with adjacent cells overlapping. Individual cells vary in both length ("apical axis") and width ("transapical axis"). *P. pungens* and *P. multiseries* are not reliably distinguished by light microscopy because they are both of approximately the same length (74-142 μm for *P. pungens* and 68-140 μm for *P. multiseries*), the same width (3.0-4.5 μm for *P. pungens* and 4-5 μm for *P. multiseries*), with adjacent cells overlapping by one-third or more of cell length. The primary accepted way for distinguishing *P. pungens* from *P. multiseries* is to count intercostal poroids, which are small holes that occur in rows between the ribs ("costae") on the inner surfaces of diatom thecae ("valves") that have been separated by treatment with acid or bleach. Since the diameters of these poroids are considerably less than 1 μm, the only way to see them well enough to count them is with scanning electron microscopy (SEM). If poroids occur in pairs in rows, then the species is *P. pungens*. If, however, there are multiple poroids (3-4) in a row, then the species is *P. multiseries*. Effectively the designation of "*Pseudo-nitzschia pungens*" in our data (obtained thus far with light microscopy only) means either *P. pungens* or *multiseries* (but we do not know which), but not *P. delicatissima* or *P. pseudodelicatissima*. The reason is that the latter two species are distinguished from *P. pungens/multiseries* by their more narrow cells (1.5-2.5 μm), compared to widths of 3-5 mm for *P. pungens/multiseries*, and by overlapping of adjacent cells in chains in *P. delicatissima* or *P. pseudodelicatissima* by only about one-ninth of cell length, compared to by one-third or more of cell length with *P. pungens/multiseries*. The differentiation of *P. delicatissima* from *P. pseudodelicatissima* is facilitated by differences in length, in that *P. delicatissima* cells are much shorter (40-76 μm length) than those of *P. pseudodelicatissima* (59-140 μm length).

Although we encountered frequent blooms of *Pseudo-nitzschia* spp. during the present study (plots in Appendix 10), at this point we do not know if toxic *Pseudo-nitzschia multiseries* occur in Buzzards Bay. In order to discern this, we would have to perform SEM analyses, which are laborious and expensive. While Umass Dartmouth does have a state-of-the-art SEM facility, of which Jefferson Turner is Managing Director, confirmation that *Pseudo-nitzschia* spp. from Buzzards Bay include the toxic *P. multiseries* remains to be done. Nonetheless, *Pseudo-nitzschia* spp. repeatedly were recorded in the present study at abundances of 20-60 x 10^3 cells l^{-1} and it is possible if not likely that some of these cells *were P. multiseries*. While these abundances are well below the Canadian threshold of 10^5 cells l^{-1} that prompts increased vigilance for domoic acid in shellfish, it is apparent that phytoplankton monitoring for *Pseudo-nitzschia* spp. should probably continue in Buzzards Bay. The need for continued monitoring is also suggested by the fact that the MWRA (Massachusetts Water Resources Authority) monitoring in Massachusetts and Cape Cod Bays encountered a bloom of *Pseudo-nitzschia* spp. (counted by David Borkman) with abundances (0.82 x 10^5 cells l^{-1}), nearly approaching the Canadian threshold of 10^5 cells l^{-1} in November, 1998. This bloom occurred one month after termination of DEP-funded sampling in Buzzards Bay.

Dinoflagellates were rarely abundant in the present study, comprising means of < 1% of total cells. However, there were numerous sporadic blooms (plots in Appendix 10), and maximum dinoflagellate percentage composition occasionally reached as much as 18% of total cells, usually at Station 8 in the inner harbor of New Bedford. Although numerous dinoflagellate taxa were recorded, the primary one of

societal interest is *Alexandrium tamarense*, which can produce PSP (paralytic shellfish poisoning) toxins. Although *A. tamarense* were sporadically recorded throughout the survey, abundances were usually low (hundreds of cells per liter) outside the inner harbor of New Bedford. However, occurrences of this species at Station 8 within the inner harbor were more frequent than outside it, and abundances were occasionally in the range of thousands, rather than hundreds of cells per liter. This confirms the repeatability of summer blooms of *A. tamarense* such as that initially recorded for summer 1988. Again, this suggests that phytoplankton monitoring for this and other potentially harmful phytoplankton species in Buzzards Bay should be continued.

Discussion

Buzzards Bay is conducive to high phytoplankton production for several reasons. Due to shallow depths, the euphotic zone extends to the bottom for most of the year (Turner & Borkman 1992). Thus, even though vertical mixing of the water column is frequently complete, shallow depth ensures that critical depth criteria (Sverdrup 1953) are usually met. Mixing also facilitates bottom-up benthic-pelagic coupling. The sediments act as a nutrient pump injecting remineralized inorganics, particularly ammonium, to the water column (Banta et al. 1990). Thus, it is no surprise that ammonium averaged 76% of total dissolved inorganic nitrogen throughout the bay. Since nitrogen is usually the primary limiting nutrient in marine systems (Ryther & Dunstan 1971), the nitrogen-replete conditions coupled with adequate light allow abundant phytoplankton growth throughout the year in Buzzards Bay. In this respect, Buzzards Bay is similar to other nearby shallow well-mixed estuaries such as Narragansett (Smayda 1983, 1984) and Peconic Bays (Turner et al. 1983), but unlike deeper summer-stratified coastal systems such as Long Island Sound (Conover 1956), Massachusetts and Cape Cod Bays (Townsend et al. 1991), and Georges Bank (Riley 1941).

Buzzards Bay exhibits large seasonal and interannual variations in levels of certain parameters. These were particularly apparent for nitrate, silicate and phytoplankton abundance and composition. Other parameters showed more uniform distributions, with the exception of the two stations in New Bedford Harbor. Distributions of phosphate and chlorophyll *a* had concentrations that were generally similar bay-wide on a given day, and over seasons and years for Stations 1-6. However, the signals for elevated concentrations of ammonium, phosphate, and chlorophyll *a* at Station 7, the sewage outfall, were apparent. High concentrations of these parameters would be expected to reflect sewage effluent, and these data clearly identify the New Bedford sewage outfall as the major eutrophication insult to Buzzards Bay prior to conversion to secondary treatment. However, the increased water transparency and decreased levels of ammonium, bacterioplankton, rod-shaped bacteria after conversion to secondary treatment clearly indicate improved water quality at the sewage outfall. Similarly, Borkman & Smayda (1998) documented a significant increase in Secchi-disk depth in Narragansett Bay from 1972 – 1996 associated with reduced suspended solids due to improved wastewater treatment.

Even though nutrient levels were usually lower in the New Bedford inner harbor than at the sewage outfall, chlorophyll *a* levels at Station 8 were generally the highest of any of our stations. We suspect that the reason for this is physical. The hurricane dike across the mouth of the inner harbor almost completely encloses it, creating somewhat of a "marine lake." Salinities behind the hurricane dike are typically 1-4 $^{o}/_{oo}$ lower than for the rest of the bay, and except for winter, surface temperatures are 1-3^{o}C higher. Although we are unaware of any substantial study of water exchange between the inner harbor and the rest of the bay, we suspect that circulation is greatly reduced. Thus, phytoplankton and nutrients appear to accumulate in the inner harbor, causing higher chlorophyll *a* concentrations there. Additional anecdotal evidence supports this suggestion. Green "blobs" of phytoplankton are frequently collected by zooplankton nets in the inner harbor, when not collected elsewhere on the same day. Cursory examination of such live samples after cruises often reveals that chain-forming diatoms blooming in the inner harbor are not apparent throughout the rest of the bay on the same day, but sometimes these taxa were present bay-wide the month before. This suggests that blooms persist longer in the inner harbor than elsewhere, again, indicating reduced water exchange.

Phytoplankton abundances recorded here are higher than generally reported from previous studies in other coastal waters of New England, and higher than for the only previous study in Buzzards Bay. The reason for the former is that our preservation of samples with Utermohl's solution did not destroy the delicate microflagellates and phytoflagellates which so completely dominated phytoplankton abundance. Most other studies of phytoplankton abundance in New England coastal waters have used formalin as a preservative, thus destroying the microflagellates, and biasing records in favor of diatoms and thecate

dinoflagellates which survive formalin preservation. The major exceptions to this generalization are phytoplankton studies in Narragansett Bay which also used Utermohl's or similar Lugol's solution, or examined unpreserved samples, and found that small microflagellates were also abundant at most times (Durbin et al. 1975). However, Borkman (1994) also used Utermohl's preservation, and reported a range of phytoplankton abundance for our Stations 1-8 in Buzzards Bay (Cruises 1-17; 1987-1988) of 0.06 – 4.98 x 10^6 cells l^{-1} (mean = 0.54 x 10^6 cells l^{-1}). This range is considerably lower than that recorded here (0.012 – 26.0 x 10^6 cells l^{-1}) for Cruises 18-141 (1988-1998).

We suspect that the reason for this discrepancy is that Borkman (1984) counted phytoplankton at 250 x, with occasional examination at 500 x to observe certain taxonomic features needed for identification, whereas Jean Lincoln (this report) counted microflagellates at 500 x (using the same microscope as Borkman used on the main campus of UMass Dartmouth) or a similar microscope at 400 x at the Center for Marine Science and Technology (CMAST). Since phytoplankton samples from Buzzards Bay are usually loaded with extraneous detrital and mineral particles, which can frequently obscure small phytoplankton cells in the 2 µm-diameter size range, we suspect that Borkman (1984) may have underestimated the abundance of microflagellates (making counts at 250 x) compared to values presented here, counted at 400 x or 500 x. However, abundances of larger diatom and dinoflagellate cells should be comparable, since both Borkman (Cruises 1-17) and Lincoln (Cruises 18-141) counted these larger cells at 200-250 x.

The bay-wide patterns for silicate suggest the possibility of biological control of silicate levels due to variations in silicate utilization by phytoplankton. Since diatoms are the dominant phytoplankters utilizing silicate, and summer dominance by non-silicate-utilizing microflagellates and dinoflagellates is a common pattern in estuaries of the northeastern United States (Durbin et al. 1975, Smayda 1983, Turner et al. 1983, Karentz & Smayda 1984), the possibility is raised that summer silicate increases in Buzzards Bay were due to differential utilization of silicate due to changes in phytoplankton community composition.

Phytoplankton community analyses suggest that silicate levels generally decline from early to mid-summer highs in response to a late summer phytoplankton blooms. These blooms are typically composed of the diatom *Skeletonema costatum* Thus, the typical late-spring to early-summer spikes in silicate levels frequently coincided with the seasonal zenith in dominance by microflagellates and dinoflagellates, and annual nadir in diatom dominance. These patterns are apparent when comparing silicate levels and percentage of the phytoplankton comprised by diatoms (Fig. 4 & 5), where periods of diatom dominance are seen to occur at low levels of silicate, and vice versa.

In conclusion, Buzzards Bay appears to be a favorable habitat for phytoplankton in that it is well-mixed and -illuminated, and nutrient-replete. Although there were obvious eutrophication signals from the New Bedford sewage outfall prior to secondary treatment, in terms of high ammonium and chlorophyll *a*, and low light penetration, the rest of the estuary appears relatively unimpacted. As with hydrography and bacterioplankton abundance (Turner & Borkman 1992), nutrients and phytoplankton pigments were highly variable in time and space. While most locations away from New Bedford Harbor exhibited similar values on a given day, the stations at the sewage outfall (7) and inner harbor (8) usually had much higher values than the rest of the bay. There were also major fluctuations in nutrients and phytoplankton pigments on time scales ranging from biweekly to monthly to seasonal to interannual. Although much of this fluctuation appeared due to physical forcing, some such as silicate appears to be biologically-driven. Consideration of parameter variability in Buzzards Bay is essential for proper understanding and management of this system.

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Figure Legends

Fig. 1. Location of sampling stations in Buzzards Bay.

Fig. 2. Surface temperatures cruises 1-141. Data points are means of the 8 stations for each cruise, and vertical lines are ranges.

Fig. 3. Secchi disk depths at Station 7, the New Bedford sewage outfall, cruises 1-141. Note the increase in secchi disk depths (ie. Water transparency) beginning with cruise 116 (vertical line) after conversion to secondary treatment.

Fig. 4. Time sequence of mean percentage of total phytoplankton abundance comprised by diatoms (thick lines) for Stations 6, 7, & 8, Cruises 18-141, versus mean surface silicate concentrations (thin lines) at the same stations, Cruises 1-141.

Fig. 5. Scatter plot of mean percentage of total phytoplankton abundance comprised by diatoms for Stations 6, 7, & 8, Cruises 18-141, versus mean surface silicate concentrations at the same stations.

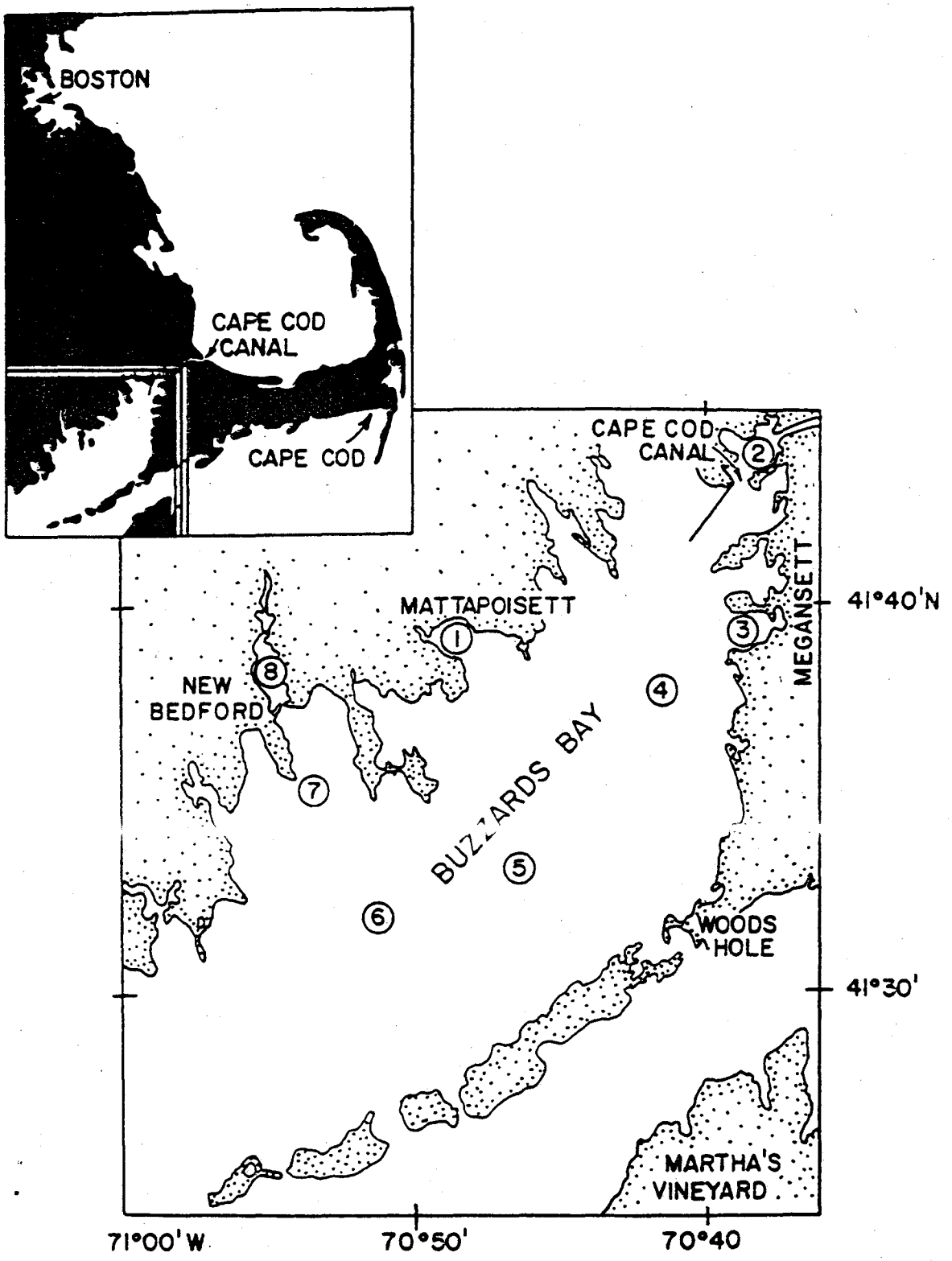
BOSTON
CAPE COD CANAL
CAPE COD
CAPE COD CANAL
MATTAPOISETT
NEW BEDFORD
BUZZARDS BAY
MEGANSETT
WOODS HOLE
MARTHA'S VINEYARD
41°40'N
41°30'
71°00'W
70°50'
70°40
1
2
3
4
5
6
7
8

Figure 1

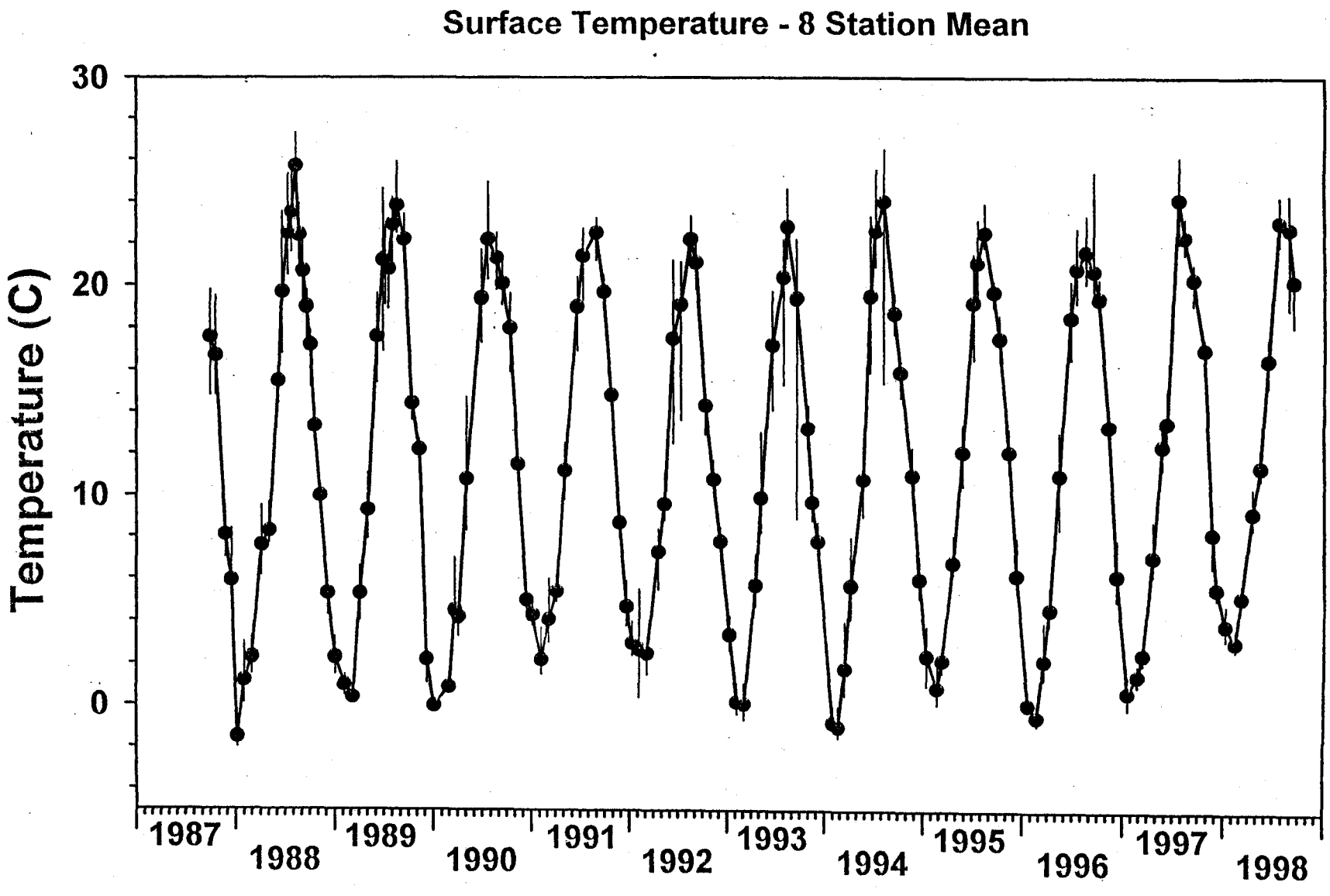
Surface Temperature - 8 Station Mean
Temperature (C)
30
20
10
0
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998

Figure 2

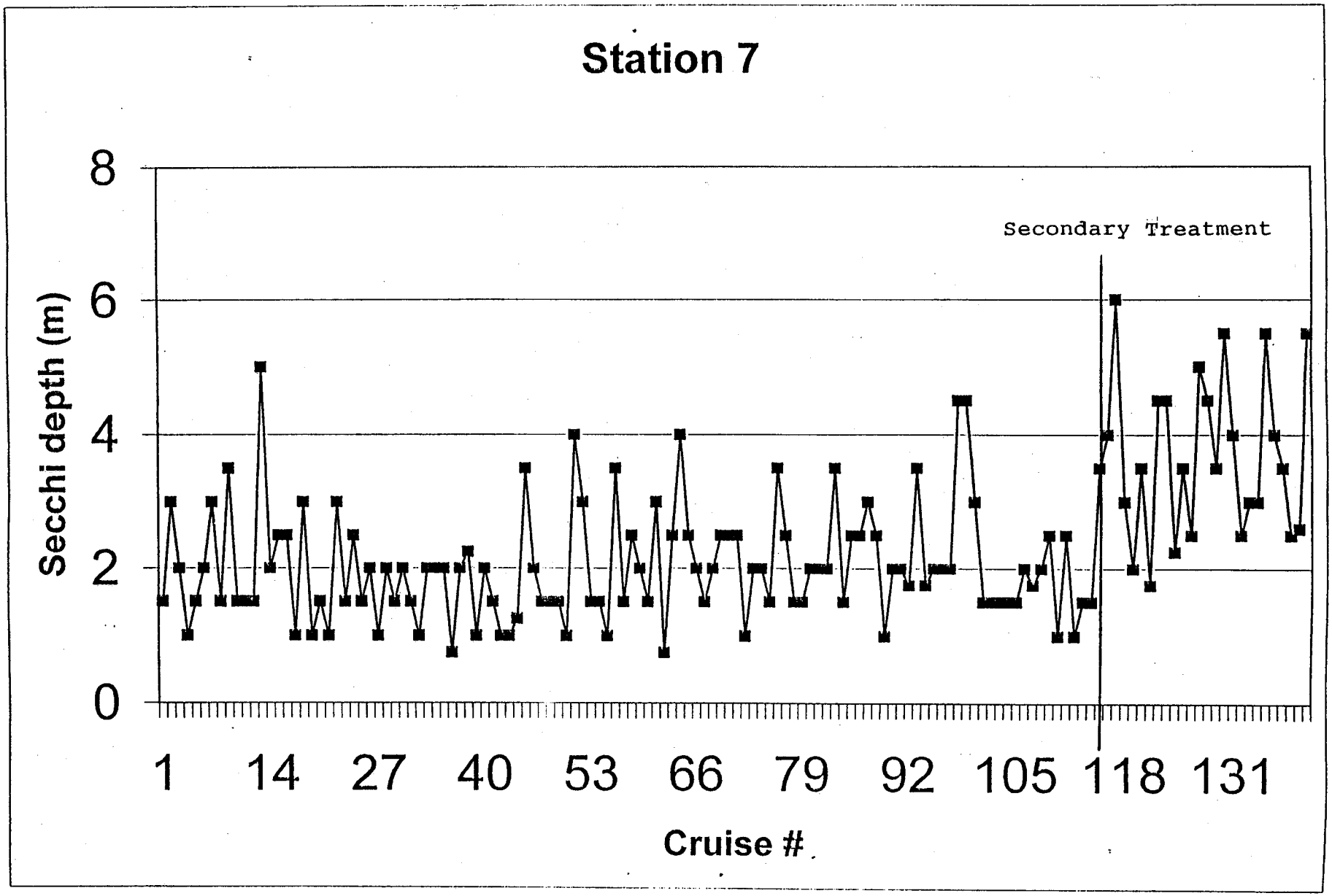
Station 7
Secondary Treatment
Secchi depth (m)
0
2
4
6
8
1
14
27
40
53
66
79
92
105
118
131
Cruise #

Figure 3

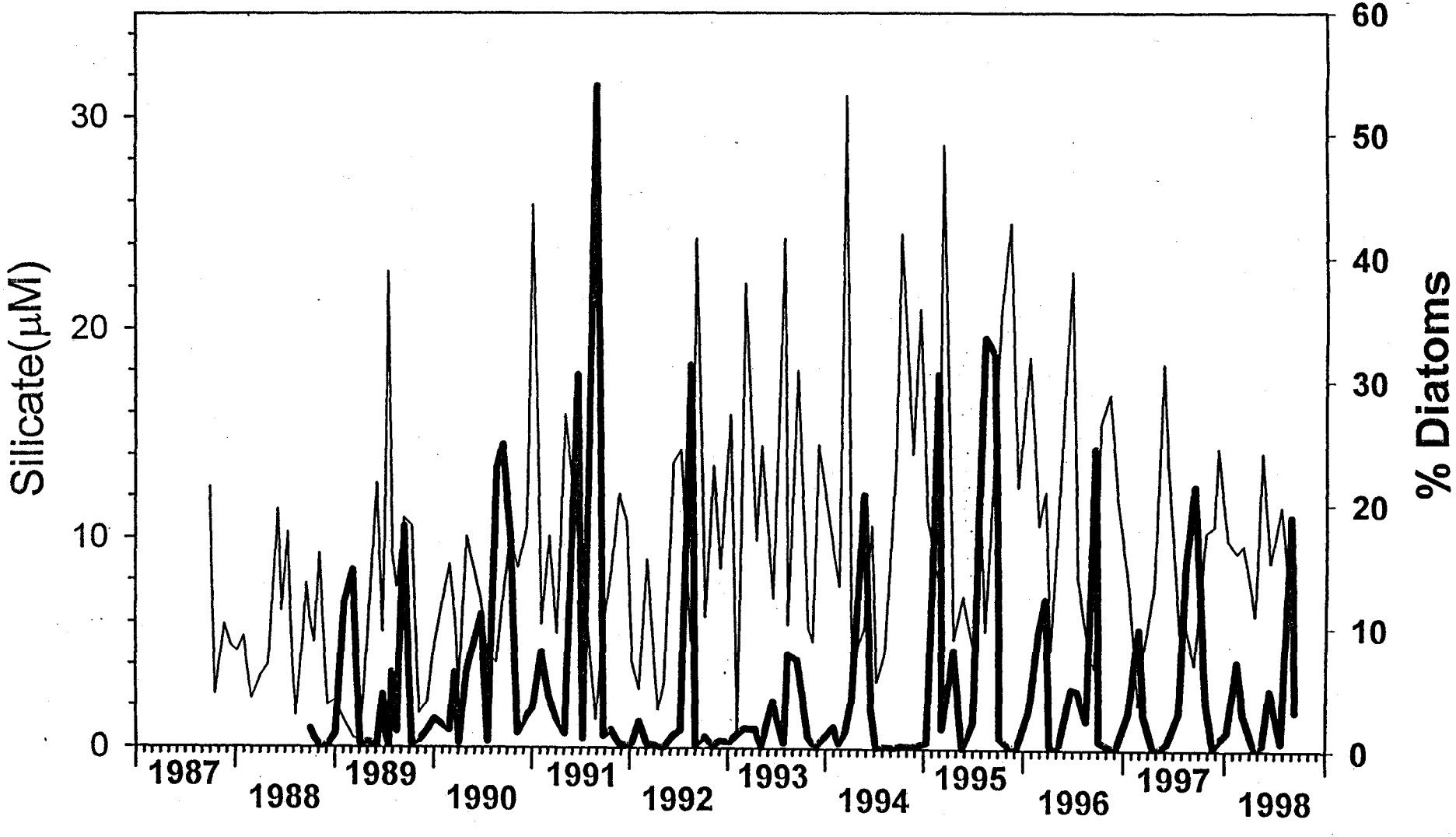
Silicate(µM)
0
10
20
30
% Diatoms
0
10
20
30
40
50
60
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998

Figure 4

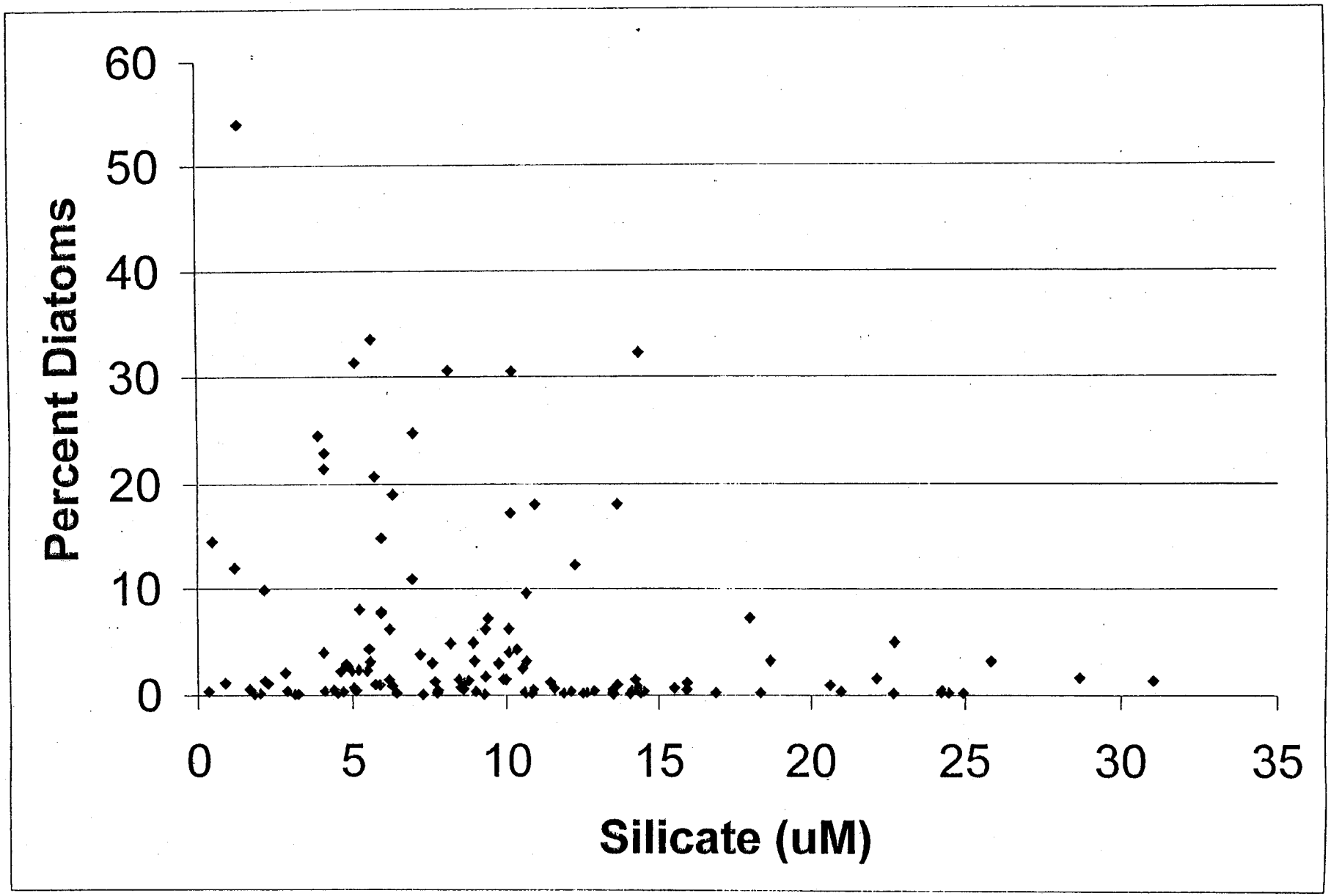
Percent Diatoms
60
50
40
30
20
10
0
0
5
10
15
20
25
30
35
Silicate (uM)

Figure 5

Table 1. Cruise Numbers and Dates for Buzzards Bay Monitoring

Cruise	Date	Cruise	Date	Cruise	Date
01	01 Oct 87	51	05 Mar 91	101	20 May 95
02	20 Oct 87	52	02 Apr 91	102	29 Jun 95
03	24 Nov 87	53	02 May 91	103	14 Jul 95
04	16 Dec 87	54	18 Jun 91	104	09 Aug 95
05	08 Jan 88	55	09 Jul 91	105	12 Sep 95
06	02 Feb 88	56	27 Aug 91	106	03 Oct 95
07	01 Mar 88	57	24 Sep 91	107	07 Nov 95
08	05 Apr 88	58	22 Oct 91	108	05 Dec 95
09	03 May 88	59	21 Nov 91	109	18 Jan 96
10	07 Jun 88	60	18 Dec 91	110	19 Feb 96
11	21 Jun 88	61	09 Jan 92	111	15 Mar 96
12	13 Jul 88	62	04 Feb 92	112	04 Apr 96
13	27 Jul 88	63	03 Mar 92	113	09 May 96
14	10 Aug 88	64	14 Apr 92	114	20 Jun 96
15	23 Aug 88	65	07 May 92	115	12 Jul 96
16	06 Sep 88	66	09 Jun 92	116	15 Aug 96
17	20 Sep 88	67	07 Jul 92	117	12 Sep 96
18	04 Oct 88	68	13 Aug 92	118	01 Oct 96
19	18 Oct 88	69	01 Sep 92	119	05 Nov 96
20	08 Nov 88	70	06 Oct 92	120	04 Dec 96
21	06 Dec 88	71	05 Nov 92	121	15 Jan 97
22	03 Jan 89	72	01 Dec 92	122	20 Feb 97
23	07 Feb 89	73	06 Jan 93	123	11 Mar 97
24	09 Mar 89	74	04 Feb 93	124	15 Apr 97
25	04 Apr 89	75	02 Mar 93	125	19 May 97
26	02 May 89	76	13 Apr 93	126	04 Jun 97
27	06 Jun 89	77	03 May 93	127	17 Jul 97
28	27 Jun 89	78	15 Jun 93	128	07 Aug 97
29	06 Jul 89	79	27 Jul 93	129	09 Sep 97
30	18 Jul 89	80	10 Aug 93	130	19 Oct 97
31	01 Aug 89	81	14 Sep 93	131	18 Nov 97
32	17 Aug 89	82	26 Oct 93	132	04 Dec 97
33	13 Sep 89	83	11 Nov 93	133	07 Jan 98
34	11 Oct 89	84	02 Dec 93	134	11 Feb 98
35	08 Nov 89	85	29 Jan 94	135	05 Mar 98
36	06 Dec 89	86	18 Feb 94	136	16 Apr 98
37	03 Jan 90	87	14 Mar 94	137	14 May 98
38	27 Feb 90	88	05 Apr 94	138	10 Jun 98
39	20 Mar 90	89	20 May 94	139	22 Jul 98
40	03 Apr 90	90	16 Jun 94	140	26 Aug 98
41	01 May 90	91	06 Jul 94	141	11 Sep 98
42	26 Jun 90	92	04 Aug 94		
43	20 Jul 90	93	13 Sep 94		
44	21 Aug 90	94	05 Oct 94		
45	11 Sep 90	95	16 Nov 94		
46	11 Oct 90	96	13 Dec 94		
47	08 Nov 90	97	10 Jan 95		
48	11 Dec 90	98	18 Feb 95		
49	03 Jan 91	99	07 Mar 95		
50	05 Feb 91	100	15 Apr 95		

Table 2. Means and ranges for water transparency, bacterioplankton, dissolved oxygen, and chlorophyll *a* and nutrient data. DIN refers to Dissolved Inorganic Nitrogen (Nitrate + nitrite + ammonium).

Parameter	Units	Stations	Mean	Maximum	Minimum
Secchi depth	meters	1-6	4.3	12.0	1.5
		7	2.3	6.0	0.8
		8	2.9	5.5	1.0
		All	3.9	12.0	0.8
% of water column in euphotic zone	%	1-6	94.65	100.00	45.73
		7	82.48	100.00	34.29
		8	90.48	100.00	40.00
		All	92.61	100.00	34.29
Bacterioplankton	10^6 cells ml^{-1}	1-6	2.26	10.28	0.18
		7	3.61	10.92	0.39
		8	3.49	9.95	0.41
		All	2.58	10.92	0.18
Dissolved oxygen	$mg\ l^{-1}$	6	9.3	13.6	2.0
		7	9.3	13.8	3.0
		8	9.1	14.1	2.8
Chlorophyll *a*	$\mu g\ l^{-1}$	1-6	5.00	22.37	0.10
		7	6.69	27.65	0.79
		8	12.84	64.66	0.92
		All	6.19	64.66	0.10
Nitrate + nitrite	µM	1-6	0.81	6.57	0.00
		7	1.13	9.40	0.04
		8	1.03	4.34	0.04
		All	0.87	9.40	0.00
Ammonium	µM	1-6	2.60	26.77	0.00
		7	6.97	70.53	0.14
		8	4.09	19.72	0.00
		All	3.35	70.53	0.00
Total DIN ($NO_3 + NO_2 + NH_4$)	µM	1-6	3.36	29.85	0.00
		7	8.05	70.68	0.16
		8	5.07	22.44	0.64
		All	4.16	70.68	0.00
NH_4 as % of Total DIN	%	1-6	75.37	> 99	< 0.1
		7	81.22	"	"
		8	75.25	"	"
		All	76.08	"	"
Silicate	µM	1-6	6.47	70.11	0.10
		7	8.63	36.82	0.20
		8	9.05	61.34	0.10
		All	7.07	70.11	0.10
Phosphate	µM	1-6	0.66	8.02	0.00
		7	2.58	27.03	0.08
		8	1.67	8.86	0.10
		All	1.04	27.03	0.00

Table 3. Summary of phytoplankton abundance and percentage composition data, Cruises 18-141.

units= cells/liter

	Station 6	Station 7	Station 8
Total Phytoplankton			
Mean	3,064,872	5,108,903	5,353,273
Maximum	9,745,246	16,351,996	26,040,130
Minimum	12,535	665,361	1,278,608
Microflagellates			
Mean	2,643,756	4,029,009	3,535,355
Maximum	5,843,154	9,274,098	12,637,355
Minimum	479,139	644,950	688,587
Phytoflagellates			
Mean	341,447	485,900	922,896
Maximum	1,592,839	2,690,176	9,409,072
Minimum	0	0	0
Diatoms			
Mean	96,516	585,887	748,842
Maximum	4,041,198	11,272,970	10,169,242
Minimum	1,102	282	0
Dinoflagellates			
Mean	2,808	4,951	74,875
Maximum	29,474	50,590	2,189,452
Minimum	0	0	0
Other			
Mean	1,496	3,156	71,305
Maximum	72,787	180,439	4,779,362
Minimum	0	0	0

units=%total phytoplankton

	Station 6	Station 7	Station 8
Microflagellates			
Mean	85.96	84.33	73.54
Maximum	99.85	99.92	99.87
Minimum	33.13	30.32	24.48
Phytoflagellates			
Mean	10.69	9.70	16.50
Maximum	61.28	60.63	60.58
Minimum	0.00	0.00	0.00
Diatoms			
Mean	2.92	5.79	8.03
Maximum	90.41	68.94	70.12
Minimum	0.05	0.01	0.00
Dinoflagellates			
Mean	0.17	0.10	0.92
Maximum	8.22	1.72	18.27
Minimum	0.00	0.00	0.00
Other			
Mean	0.05	0.07	1.01
Maximum	2.40	3.88	54.55
Minimum	0.00	0.00	0.00