SEASONAL TRENDS AFFECTING WATER QUALITY IN THE LOWER LAKE OF THE NEW MEADOWS RIVER ESTUARY

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Contents

INTRODUCTION

The New Meadows River Lower Lake

The New Meadows River estuary is part of the Casco Bay region of mid coast Maine, separating the towns of Brunswick and West Bath. The mudflats of this estuary, being shellfish habitats, are an important natural resource to the surrounding communities. It is speculated that the building of major roads has adversely impacted the upper portion of the estuary, which has experienced frequent low dissolved oxygen levels and recent fish kills. The northern end of the estuary has been divided into two lakes, the Upper and Lower Lakes, by the building of three major roads: Old Bath Road, which runs along the North end of the river; Bath Road, which runs along the South end of the Lower Lake; and Route 1, which divides the lakes (Fig. 1). It is thought that, among other things, these roads restrict tidal flow within the estuary (Groves, 2002). In addition, runoff from the roads could pollute the waters of the Lake.

In his report on the state of the New Meadows River, Heinig (2002) describes the negative environmental phenomena associated with the lakes. These effects are largely seasonal in nature. Periods of low oxygen generally occur in the summer, and periods of extremely high nutrients and coinciding extensive algal blooms occur yearly. In the Lower Lake is a site of particular concern: a nine-meter deep hole, which usually becomes completely anoxic during the summer (Fig. 1). This report will present and analyze water quality data gathered from this hole throughout the year from April 2002 to April 2003. The parameters monitored include: temperature, salinity, and dissolved oxygen profiles; nutrient and chlorophyll a samples; turbidity; and weather conditions. Each of these different parameters will be examined both individually and in conjunction with each other to build up a picture of the general health of the Lower Lake ecosystem, with a focus on assessing the possibility of eutrophic conditions in the hole. Special attention will also be paid to assessing seasonal effects over the course of the year.

Estuaries

Estuaries are partially enclosed water bodies protected from the direct tidal action of the open ocean, in which saline and fresh water mix, creating a unique ecosystem of high biological productivity and species diversity. The combined conditions high sunlight, low tidal action due to the sheltering land, and salinity gradient provide a variety of niches in which abundant, diverse life can flourish. In addition to supporting diverse and abundant forms of life, estuaries play an essential ecological role as nurseries for juvenile marine organisms. They are also important natural resources for human beings, due not only to their productivity, but also the natural processes by plants and microbes that filter and clean particulate and nutrient pollution (Garrison, 2002)

Estuaries make up 80% of the Atlantic coastline in North America (Pinckney et. al., 2001). Presently, water quality problems such as eutrophication pose a serious threat to estuarine environments in the United States: 65% of our nation's estuaries are eutrophic to some extent. A wide range of anthropogenic causes are implicated in this problem, among them: agriculture, urbanization, coastal development, and industrial expansion. The problem of coastal eutrophication due to anthropogenic nitrogen loading has many complex scientific, political, and social implications. The formidable challenge involved in addressing this issue is due in large part to the fact that nitrogen comes from many different sources—not only point and non-point ground runoff, but also "new," less visible sources currently coming to light, such as atmospheric deposition and groundwater discharge (Paerl, 1996).

Eutrophication

The word "eutrophic" describes an aquatic ecosystem rich in biomass and nutrients, and "eutrophication" the process by which waters become thus enriched. The excess organic material can originate from two types of sources. "Autochthonous" sources within the system are photosynthesizers such as phytoplankton and microplankton (among dominant primary producers of estuarine environments), or benthic regeneration. "Allochthonous " or outside sources include rivers or terrestrial runoff containing organic matter. Phytoplankton productivity is generally the source of organic matter most central to the eutrophication process (Pinckney, et. al., 2001).

The negative effects of eutrophication on aquatic environments are regulated mainly by nutrient enrichment. The primary nutrients involved in eutrophication are nitrogen (N) and phosphorous (P). Phosphorous is usually most important in fresh water, but Nitrogen is typically the nutrient limiting the growth of primary producers in estuarine systems. When nitrogen input exceeds a threshold level, a significant increase in phytoplankton biomass density results (also known as a "bloom"). At the surface, the photosynthetic activity of phytoplankton adds dissolved oxygen to the water column. However, when these phytoplankton die off and accumulate at the bottom, their decomposition by bacteria depletes oxygen. This effect is augmented when waters are highly stratified by temperature or salinity, causing the isolation of phytoplankton biomass and low oxygen concentrations. Hypoxic waters—waters exhibiting unusually low dissolved oxygen levels—can kill off dimersal, epibenthic, and benthic communities, which represent a great loss to estuarine ecosystems (Lowery, 1998). Oxygen depletion can also spread throughout the waters, sometimes leading to fish kills.

Nutrients

Nutrient loading is defined as the rate at which a substance such as N is added to a system (Pennock, et. al., 1992). As stated before, nitrogen is generally the primary nutrient limiting algal growth in estuarine waters (Pinckney, et. al., 2001). Nitrogen is found in various chemical forms as it cycles through aquatic systems (Garrison, 2002). Nitrogen gas (N_2) constitutes 78 percent of the air we breath. Relatively large amounts of the gas are dissolved in marine waters; however, the free nitrogen needs to be "fixed"—either bound to oxygen to form nitrate (NO^-_3) or nitrite (NO^-_2), or bound to hydrogen to form ammonium (NH^+_4) —before it can be used by organisms. This task is performed nitrifying bacteria or cyanobacteria. However, nitrate and nitrite are also introduced into the ocean through terrestrial sources, so that plankton can take it up directly. When these plankton die and sink to the bottom, denitrifying bacteria decompose the biomass and convert the fixed nitrogen to dissolved N_2**.**

A significant amount of nitrogen can be regenerated within the system by heterotrophic microorganisms through the microbial loop process, in which protozoa graze on bacteria and produce waste containing ammonium, a usable nutrient source for algae (Pinckney, et. al., 2001). The ratio of new nitrogen added from outside sources, usually in the form of nitrate and nitrite, to total dissolved inorganic nitrogen (DIN) including the regenerated product (ammonium) is known as the *f*-ratio (Gilpin, 2000).

Despite the fact the NO3 must be broken down into ammonium as part of the assimilation process, NO3 is often associated with the spring diatom bloom. Nitrogen can be regenerated in the surface waters (after phytoplankton decay) and turned back into NH4, which is why ammonium is associated with regenerative processes (Gilpin, 2000). As already stated, nitrate and nitrite are the predominant forms associate with terrestrial sources, or outside input. The nitrogen entering the euphotic zone from outside sources is known as new production (Gilpin, 2000). This report will focus on the ratio of the total nitrates and nitrites to the total dissolved inorganic nitrogen (nitrates and ammonium). Thus, the ratio can show us how much of the nitrogen can be attributed to outside sources, an effect associated with eutrophic conditions.

Phosphate (PO^{3-}_4) and silicate (Si, taken up by diatoms for their shells) can also sometimes be limiting nutrients in estuaries. Different methods can be utilized to determine the limiting nutrient (Pinckney, et. al., 2001). In this project, all three nutrients were monitored. However, since nitrogen is assumed to be the limiting nutrient in this estuary, the analysis will focus on dissolved inorganic nitrogen levels and composition.

Dissolved Oxygen

Oxygen depletion in the summer is generally a common occurrence for estuaries (Kemp et. al. 1992). A study of Chesapeake Bay by Kemp et. al. found that stratification of the water column limits oxygen exchange with bottom waters in the spring and summer, when phytoplankton provide organic matter for benthic respiration. The source of the phytoplankton biomass was traced to terrestrial runoff that lead to algal blooms.

Assessing the effects of eutrophication based on DO is complicated by the fact that phytoplankton add DO to the water column through photosynthesis. In addition, DO is consumed both within the water column and also within the sediments through organismal respiration (Clark, et. al. 1995). In addition, nutrient loading does not necessarily lead to hypoxic conditions. According to Pinckney et. al. (2001), the results of nutrient loading on estuarine ecosystems depends on the particular characteristics of that estuary: surface area, depth, volume, flushing rate, water residence time, tidal exchange, vertical mixing, and stratification. According to Pennock et. al. (1992), lots of mixing due to tides can mitigate the oxygen-depleting effects of nutrient enrichment, in addition to salinity and temperature-induced stratification described by Lowery (1998).

Chlorophyll

Chlorophyll levels in the water are indicative of the amount of phytoplankton biomass—thus, correlations between high chlorophyll and nutrient levels can be indicative of eutrophic conditions which, as stated before, often involve a drastic increase in algal biomass (Litaker, et. al., 1987). We will therefore be looking for the unusually high chlorophyll levels that could signify a phytoplankton bloom.

Suspended sediments, or turbidity, affects phytoplankton growth and production by reducing available sunlight, thereby limiting growth to surface waters. This in turn effects DO levels, because phytoplankton growth and production adds DO to the water column (Clark et. al., 1995). We will be looking at secchi depth as measure of turbidity and comparing it to patterns of phytoplankton growth and dissolved oxygen levels.

In this study, two different forms of chlorophyll will be analyzed: chlorophyll-a, the predominant photosynthetic pigment of phytoplankton, and phaeophytin, the breakdown product of chlorophyll. According to the Florida Department of Environmental Protection, the ratio of phaeophytin High proportions of chlorophyll a indicate rapid growth of the algal population, while high proportions of phaeophytin indicate a population in decline or stress (1999). These periods of decline correspond to conditions stressful to phytoplankton, such as prolonged overcast skies. Other parameters monitored in this study that could put stress on the algal population include high turbidity and salinity.

Salinity

The relationship of salinity to nitrogen levels and phytoplankton populations make it an important factor in assessing the effects of eutrophication. Patterns in salinity data can indicate the amount of fresh water being added to the system either by rain, rivers, or runoff, which could coincide with the increased N levels that lead to algal blooms. According to Lowery, (1998) research has also shown there to be a direct connection between salinity and N availability: the rate of uptake and assimilation of N by phytoplankton is highest in oligohaline and mesohaline waters, making these areas more likely to become eutrophic. This is connected to the fact that N-fixing cyanobacteria can grow and thrive in waters with up to 32% salinity, within the range of an estuary such as the New Meadows (Barron, et. al. 2002). Research by Barron et. al. (2002) has also shown that salinity can effect phytoplankton growth directly. If salinity in the estuary is relatively constant, then a change in salinity (either an increase or decrease) could slow phytoplankton growth. The presence of high levels of nutrients, however, could counteract this effect, because the bacteria will continue to fix N, which will promote growth. And so, nutrients are generally more important than salinity by itself in effecting phytoplankton growth (Barron, et. al., 2002). In addition to effects on phytoplankton growth, particularly important to this study will be the effect of vertical salinity stratification on augmenting the affects of eutrophication by isolating bottom waters (Pennock, et. al.).

Seasonal Effects

Since the data compiled covers the course of the entire year, from April 2002 to April 2003, seasonal factors affecting water quality will be of particular interest. The overall goal of this study will be to build up a picture of water quality patterns at the deep hole throughout the year through looking at trends and relationships between the various factors associated with eutrophic conditions. Weather patterns will also be observed in order to determine the effects of seasonal changes in rainfall, air temperature, and other parameters on the system at the deep hole.

As already mentioned, Heinig (2002) reported that the water quality problems in the New Meadows are exacerbated in the summer, when low oxygen levels and near total anoxia in the deep hole frequently occur. Spring algal blooms that can result in eutrophication are also common occurrences for temperate coastal regions (Kristiansen et. al., 2001). Thus, it is likely that a spring bloom at the Lower Lake might be related to the hypoxia occurring over the summer in the deep hole.

As stated before, vertical mixing and stratification are influenced by both temperature and salinity profiles, and stratification of the water column can augment low oxygen levels in bottom waters by limiting mixing. For this reason, dissolved oxygen profiles will be compared to temperature and salinity profiles, with consideration of seasonal effects on stratification. In addition to stratification, tides can also have a significant effect on the mixing of the water column. In their 1981 study, Demers and Legendre, 1981 found tides are important in regulating vertical mixing, and that mixing in turn regulated productivity and biomass within estuaries. Thus, tides can have an important influence over eutrophic conditions in estuaries. Groves (2002) expressed concerns that the roads involved with the Lower Lake might interfere with tidal flow within the estuary. If this is the case, it is likely that the effect of stratification might be augmented at the Lower Lake.

Another point of interest will be patterns in nutrient loading. High rainfall might be expected to coincide with an increase in nitrates and nitrites, due to increased terrestrial runoff. Since increased nitrates are generally associated with the spring bloom (Gilpin, 2000), rainfall patterns might be expected to have a significant effect on eutrophication. Ammonium could also be an important factor in regulating phytoplankton populations and, hence, eutrophication, as it is also an important nutrient source. Patterns in ammonium levels would also be important in testing the prediction by Heinig (2002) that the deep hole might be an important sight of nutrient regeneration, since ammonium is the form of nitrogen associated with regeneration. A comparison between seasonal variations in the *f*-ratio and variations in phytoplankton productivity could be important in understanding the way that nitrogen levels influence eutrophication at the Lower Lake.

METHODS

Water quality data were collected from the deep hole in the middle of the Lower Lake over the course of the year from April 2002 to April 2003. Data were collected over the course of the year by the Friends of Casco Bay and various groups of Bowdoin students. Samples were taken several times in most months, excluding only December and January. Compiling these the data from these teams, 24 sampling days total are represented over the entire year. During February and March, when the lake was frozen over with two feet of ice, samples were taken by drilling a hole in the ice with a gas-powered auger.

Ambient conditions were recorded for each sampling day. Parameters monitored included: air temperature, wind speed and direction, weather, rainfall in the previous 24 hours, number of days with similar weather, high and low tides, current tidal stage at time of monitoring, and water surface. Secchi depths were recorded as a measure of water column turbidity, except for during February and March, when there was ice cover on the lake. Profile data was collected with a YSI multiparameter data sonde, taking readings at every meter starting with the surface. The sonde was calibrated before and after each sampling session. Parameters of interest recorded by the sonde were: temperature, salinity, and dissolved oxygen levels (both in mg/L and percent saturation). pH was also monitored. Water samples were collected for nutrient and chlorophyll-A analysis using a Van Dorn bottle; samples were taken from the surface, bottom, and above and below the thermocline whenever the YSI data indicated that a significant, rapid temperature gradient was present (in many cases, bottom and below the thermocline were the same). When a thermocline was absent, samples were taken from the surface and bottom. Water for the nutrient samples was filtered in the field using a syringe and Millipore 0.45um HA membrane filters (except for February and March sampling dates, when samples were brought back to the lab for filtering); two drops of chloroform were added to the final samples before freezing them and finally sending them to the University of Maine at Orono for analysis. The chlorophyll-A water was transported back to the lab for filtering in an amber bottle on ice to prevent further photosynthesis. Fifty to 100 mL of water were filtered through 25mm Whatman glass microfibre filters using a hand pump and pressure gauge, wrapped in tin foil, and frozen. The volume filtered was recorded, and the samples were analyzed in the lab of the Friends of Casco Bay using a fluorometer.

In addition to the weather and profile data and the chlorophyll-A and nutrient samples, continuous surface data was also obtained from August to September by the Friends of Casco Bay using their YSI sonde, which included a chlorophyll sensor. The sonde was moored in the surface waters above the hole, where it collected data every hour from August 21 to September 17 2002. In addition, continuous temperature profile data was collected from February through April, 2003 using HOBO Water Temp Pro digital temperature sensors tied to an anchored rope at one meter intervals. Some of the probes were removed for part of the sampling period and then replaced with new probes.

Most of the data was compiled and graphed using Microsoft Excel, with the exception of the profile data, which was also contoured in Ocean Data View. For the profiles, only one sampling date per month was included for the sake of the clarity of the excel graphs. The chlorophyll data for the early spring (from April 19 to May 22) was obtained from the YSI chlorophyll sensor profile, rather than by discreet water sampling and testing methods used in the other cases.

Weather data for Brunswick, Maine covering the entire year was obtained from the website of the National Weather Service Forecast Office, part of the National Oceanic and Atmospheric Administration (http://www.erh.noaa.gov/er/car/climate.htm). The weather parameters considered were: average daily air temperature, total precipitation, and sky cover. These parameters were graphed using Excel.

RESULTS

Monthly YSI Profiles

Figures 2A through 2D are water column profiles measured by the YSI over the course of the year, providing a picture of seasonal trends. Surface temperatures varied from below zero degrees C in the winter to around 25 degrees in August, while bottom temperatures reached a high of around 15 degrees in September (Fig. 2A). Surface salinity varied widely, ranging from around 17 ppt in March and 19 ppt in April, 2003 to nearly 30 ppt in August, 2002, while the bottom levels were relatively constant throughout the year between 28 and 30 ppt (Fig. 2B). Surface DO levels, presented as both percent saturation and concentration in mg/L, mostly ranged from around 80 percent or 8.0 mg/L to between 100 and 120 percent or 12.0 mg/L, with the exception of two particularly low and high points in February and July (around 65 and 145 percent, respectively) (Figs. 2C, 2D). Bottom DO levels ranged from close to zero (for both measurements) up to over 80 percent, or 8.0mg/L, in October, and above 10.0 mg/L in February.

The seasonal variations in water column stratification are evident in the graphs. The water column was most strongly thermally stratified from June through August, with a pronounced thermocline (Fig. 2A). Weaker stratification was present but less pronounced in the early fall and spring, and there was almost no stratification in October 2002. The October date is particularly notable because the water column was almost completely homogenous in both temperature (Fig. 1A) and salinity (Fig. 1B); in addition, the dissolved oxygen profiles (Figs. 1C and 1D) were comparable only to February in being only slightly stratified. With the exception of October, however, seasonal trends varied between the different parameters. In the case of salinity, a pronounced halocline was present in early spring and late fall. In addition, there was a long period with a moderate halocline from July to September, with the most homogenous salinity profile in August. With the exception of these months, though, the surface salinity was generally very low relative to the rest of the water column. Extremely low surface salinity was present during the early spring of 2003.

In addition to low surface salinity, the February profile exhibited very low levels of DO at the surface relative to the rest of the water column, which maintained high DO levels. On this day, the lake was covered with about two feet of ice, and so the surface sample was taken from inside the hole drilled by the auger, which may have affected the DO levels. In general, though, the seasonal patterns for DO concentration profiles are similar to those of the other parameters. During the late spring, summer, and early fall, DO levels typically started out at the surface between around 100 and 120 percent saturation or 8 and 10 mg/L and dropped to between 10 and nearly zero percent saturation (0.5 and nearly zero mg/L) between 5.0 to 7.0 meters (with the exception of July, which started at 140 percent at the surface).

While DO stratification was generally strong during from spring to early fall, the level of stratification varied somewhat depending on how high the surface levels were, with the most rapid rate of decrease in DO with depth on April 11, 2003. Stratification with low bottom DO levels (30 percent, or 3.0 mg/L) beginning at around 5m is apparent in November and April, 2002, but the lowest levels are still notably higher than in the summer. The same drop in DO around 5m also took place in March, 2003; however, three unusual characteristics stand out in the March, '03 column, particularly in the DO concentration profile: the significant drop in DO from the surface (the highest measured levels of the year, 14 mg/L) to 1m, the elevated levels between 2 and 5 meters (around 12 mg/L), and the even more significant drop in DO from 8m to the bottom (6 mg/L to around 1 mg/L). The April, 2003 profile is even more unusual compared with the other months: the column from 1 to 4m had even higher DO levels than the surface, around 14 mg/L and 130 percent saturation on April 11 and 12 mg/L and 120 percent saturation on April 28. These elevated levels dropped off abruptly at 4m to 2 mg/L and 20 percent, and bottom levels were close to zero.

Time series of the YSI profile data from every sampling day throughout the year was displayed using the Ocean Data View oceanographic data software (Figs. 3A-3C). By blending data points into a continuum of varying shades of color, these graphs make patterns of stratification in the water column over time even more evident. The bright reds, oranges, and yellows in the temperature graph indicate high surface temperatures and strong stratification in the spring, summer, and early fall, with the most pronounced thermocline from June through August. The solid columns going from green to purple from fall to winter show decreasing water temperature with little or no stratification. Salinity in the lower portion of the water column was relatively uniform over time at typical levels of around 30 ppt, but highly stratified above 5m for much of the year. During periods of intense salinity stratification, a low-salinity lens can be observed at the surface, indicated by blue or purple (24-25 ppt). From August to October, however, the entire water column exhibited relatively uniform salinity. Stratification of dissolved oxygen is most clearly represented by the percent saturation graph. With the exception of the winter, there is consistent, pronounced stratification between high surface DO levels and extremely low bottom levels. In October, however, the water column is well-mixed. Low bottom DO level return in November (distance 0.25 km). The highest surface DO levels at the surface can be observed in July, while elevated levels just below the surface can be observed in March and April 2003.

Continuous Surface Data: August-September, 2002

Figures 4A through 4E show the continuous surface data taken from August to September for the same parameters as measured in the YSI profiles, in addition to combined chlorophyll-a and phaeophytin data. These data illustrate the day-by-day patterns of temperature, dissolved oxygen, and chlorophyll levels. The temperature range from day to night generally was rarely more than 1 degree C (Fig. 4A). Surface DO ranges between day and night varied more significantly, with the lowest range during the last week of August at less than 2.0 mg/L, and the highest ranges in during the second week of September, at around 9.0 mg/L (Figs. 4C-D). Chlorophyll-a ranges varied even more drastically, with ranges of around 2 ug/L frequently punctuated by huge daytime spikes, the highest spike being on September 9, from between 0 and 2 ug/L to around 19ug/L—a range of at least 17 ug/L (Fig.4E).

Beyond daily temperature cycles, a general trend can be observed of decreasing temperature from mid August to mid September, from around 26 to between 19.5 and 21 degrees C (Fig. 4A). This decrease is interrupted, however, by a spike in surface temperature during the week of 9/7 to 9/14 to a high of nearly 25 degrees. Salinity remained relatively constant at around 32 ppt until 9/5, at which point it began to steadily decline from around 31-32 ppt to around 27 ppt (Fig. 4B). Overall DO levels ranged from 20 to 175 percent saturation (0.5 to 12.0 mg/L) (Figs. 4C-D). The high points in this range occurred after the first week in September, with the low points in the range occurring a few days later. The chlorophyll patterns are similar to DO patterns in that most drastic ranges from day to night occurred between the first and second weeks in September, with the highest points also occurring during this period (12, 14, and 19 ug/L) (Fig. 4E). In contrast to the DO data, however, there was a general trend of the daily low points in surface chlorophyll levels dropping down to zero in the beginning of September and remaining there through the rest of the sampling period.

Continuous Temperature Profile: Winter, 2003

Figures 5A and 5B depict continuous temperature profile readings taken from February 14 through April 28, 200 in both Excel and Ocean Data View formats. As can be seen in these graphs, temperatures fluctuated much more widely at the surface than throughout the rest of the column. From February 14 to March 7, surface temperature ranged from –3 to –1 degrees C, while temperatures throughout the rest of the column were relatively constant around –1 degree, with little variation or stratification. Temperatures 1 to 5m diverged little from each other, while temperature tended remained relatively constant at 6 and 7m. The upper portion of the column experienced a significant drop in temperature that reached its low point on Feb. 18, which hardly affected the bottom of the column.

In general, the bottom temperature fluctuated very little, exhibiting a gradual, linear trend of increasing temperature with time, from –1 to 2 degrees at the end of the sampling period. Around the middle of March, surface temperatures began to once again rise above bottom levels. From around March 20 to the beginning of April, temperatures at 1 and 4m followed each other and climbed steadily, while surface temperatures fluctuated widely from 0 up to as high as 3 degrees. After the beginning of April, temperatures at 4m dropped down to follow 7m temperature trends, while 1m proceeded to follow 0m trends, climbing beyond 5 degrees. Probes were reattached at 2, 3, and 5m on April 11, after which they generally followed trends at the surface. After April 11 the rate of the increase in temperature with time was inversely proportional to the depth of the probes, with a pronounced separation in temperature between 5m and 6m that increased over time. By April 28, there was 11 degree difference between the temperatures at 0m (13 degrees) and 8m (2 degrees), and a 5 degree difference between temperatures at 5m (8.5 degrees) and 6m (3.5 degrees).

Nutrients

Nutrient levels measured at each sampling day are shown in Figures 6A through 6E. Total dissolved inorganic nitrogen (DIN) levels at the surface were fairly constant at low to undetectable levels on the scale of the graph from May through October, but reached 10 uM and above in April '02, November '02, and February '03 (Fig. 6A). Bottom levels were comparable to surface levels during these three months. Samples taken above the thermocline rose slightly between June and July, and suddenly reached high levels in August at 60 uM. During the summer, when a thermocline was present, very high DIN levels (up to 120.00 uM) generally alternated between the region below the thermocline and the bottom, after which they dropped off. Levels then rose by November 26 at the surface and bottom to around 10 and 28 uM, respectively (no thermocline was present), and were still elevated in February.

Comparing Fig. 6A to Figs. 6B and 6C, we can examine the compound-specific makeup of the total DIN, or the proportions of combined nitrates and nitrites to ammonium. Because ratios between the two types of compounds are graphed, the two graphs mirror each other. In general, DIN was made up almost entirely of ammonium, despite a spike in the proportion of nitrate to nitrite ratio at the bottom toward the end of May, as well as a far more pronounced one at the beginning of July at the surface (and also above the thermocline somewhat), a lesser one in August, and a complete shift in the ratio by the third week in October. From this, we can see that the spike in DIN toward the end of May was due to an increase in nitrates and nitrites, rather than ammonium (Fig. 6A). Similarly, the elevated surface and bottom DIN in November and February was fairly equally divided between ammonium and combined nitrate and nitrite, while surface DIN was predominantly made up of nitrate and nitrite.

Large increases in phosphate levels occurred in the lower portion of the water column, from levels below 10 uM up above 40 and even 70 uM (Fig. 5D). The spike in phosphate levels around the end of May and beginning of June coincides with the general spike in DIN (and the nitrate/nitrite proportion relative to ammonium, Fig. 6A). The two major increases in phosphate levels took place at the beginnings of June and September, with the most significant increase at the bottom from the middle of July to August (a similar increase in DIN took place at the bottom over the same period, Fig. 6A), and then dropping off by the third week of October and remaining at low levels through February, 2003. Silicate levels generally followed the same patterns as phosphate, with a notable exception: the huge spike in silicate levels at both the surface and bottom on November 26 (Fig. 6E).

Chlorophyll-a and Phaeophytin

Combined chlorophyll-a and phaeophytin levels are shown in Fig .7A. The most notable data points are: the high levels above the thermocline in August (close to 140 ug/L), accompanied by a more moderate increase at the surface to above 40 ug/L; at the bottom around the beginning of October (around 110 ug/L); and at the bottom in February (115 ug/L). Lowest levels (close to zero) occurred at both the surface and bottom in May 2002, and at the surface and below the thermocline in April 2003. Above thermocline levels were generally highest. There were two other more moderate spikes in chlorophyll-a and phaeophytin levels in July, with measurements above the thermocline reaching close to 60 ug/L. The above and below thermocline levels rose together first, followed by an increase at the surface and then at the bottom. The increase at the bottom coincided with the second spike above the thermocline. While levels in April 2002 and the end of October 2002, were not very high on the scale of the graph, they were nonetheless elevated. Levels above 15ug/L occurred at the surface and bottom in April, when no thermocline was present, and surface levels climbed to nearly 20 ug/L toward the end of October.

Phaeophytin data is graphed individually in Fig. 7B, although data was not available before June. Phaeophytin levels were low up until the end of July, excepting the spike at the surface on July 7. Above thermocline levels were extremely high from August through October 2 (from 100 to 275 ug/L), during which the data closely followed the patterns of total pigment levels. A spike at the bottom also occurred on October 2 (over 225 ug/L). Then, around October 9, phaeophytin levels dropped off again. With the exception of the spike at the bottom in February 2003 (75 ug/L), levels remained low throughout April 2003.

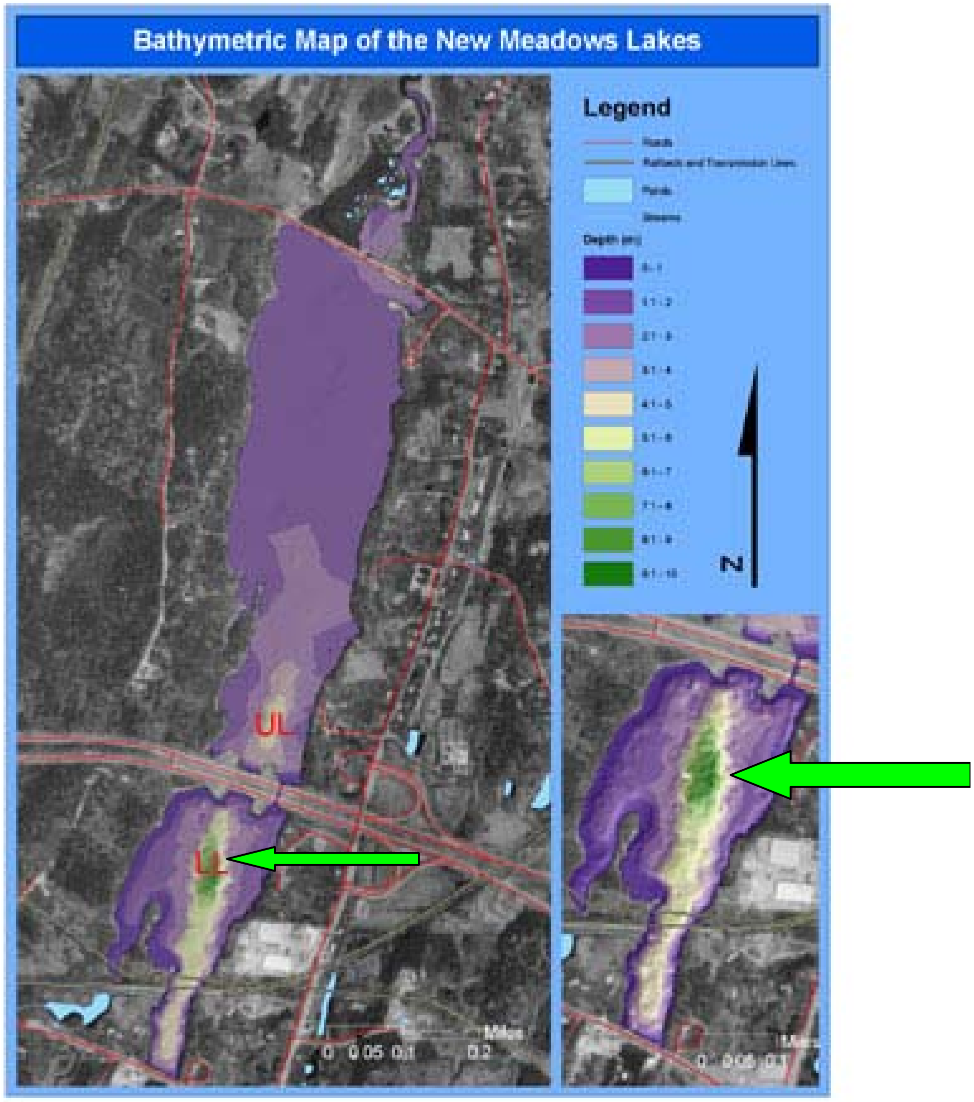
Turbidity

Fig. 8 shows the variations in the turbidity of the water as measured by secchi disk depth. Increased disk depth correlates with increased water clarity. Particularly deep readings occurred on 9/18, 10/09, 10/23, 11/26, and 4/11/03, with the deepest reading on 4/11 at nearly 3.75 m. Turbidity was greatest in July and August, with the lowest readings on 7/29 and 8/6 at less than 1.5 m disk depth. Secchi data for February and March 2003 could not be obtained due to ice cover. Turbidity was very low in April 2003, with secchi depths of over 3m.

Weather

Weather data for Brunswick, ME as represented by average daily temperature, precipitation, and cloud cover is shown in Figs. 9A through 9C. Daily temperature predictably increased over the summer months and decreased steadily over the fall and winter months, beginning to rise rapidly again by February. The highest temperature (around 85 degrees C), was reached around the first of June, and the lowest in February (below 0 degrees C) (Fig. 9A). Precipitation over 24-hour periods was frequent throughout April, May, and the first half of June, 2002, although the amount of daily rainfall in inches was not especially high relative to yearly highs (Fig. 9B). There was a period of very low precipitation during the month of August, followed by two periods of high precipitation in mid-Sept (1.5in.) and relatively high rainfall in Oct (0.5-1in.). November saw one of the heaviest rainfalls of the year (2in.) towards the beginning of the month. The highest amount of precipitation, however, occurred toward the end of January, at over 3 inches. High levels of precipitation preceded February 14, when surface salinity was very low. More high points (from 1-1.5 in.) occurred toward the end of February 2003 and beginning of March, as well as the beginning and end of April 2003. Cloud cover fluctuated relatively regularly throughout the year between low and total cover (Fig. 9C). Notable periods included a long period of intermediate cover through the first half of July, a period of very low cloud cover between August and September (the same period with no precipitation) and a period of high cover around the beginning of April, 2003.

Fig.1: Map of New Meadows Lakes



9-meter hypoxic hole at Lower Lake

Fig. 1. Bathymetric map of the New Meadows Lakes, Brunswick, ME.

Depicts three major roads involved with the Lakes and the two sampling sites designated as UL (Upper Lake) and LL(Lower Lake). Deep hole sampled for this study appears under the designation LL, and is shown in greater detail in the right-hand image. The color-coding illustrates that the LL site is by far the deepest region in the Lakes (~9m).
(obtained from http://academic.bowdoin.edu/courses/f02/geo103/nml_map.shtml, accessed 4/17/03).

Figures 2A-2D: YSI Water Column Profiles

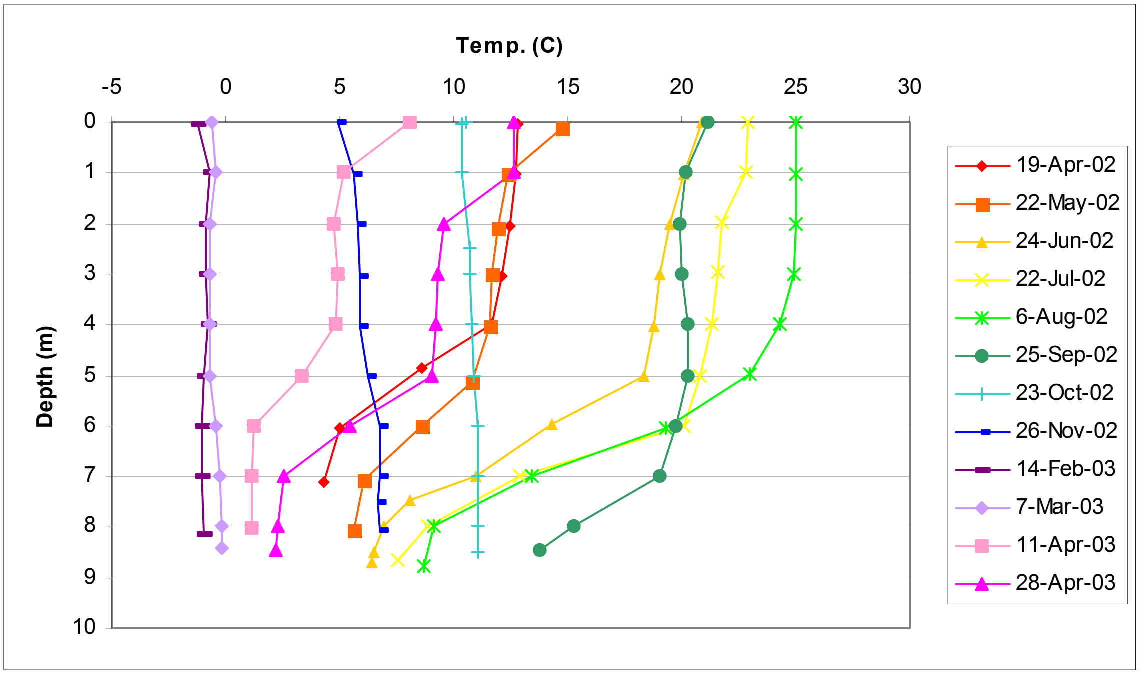


Fig. 2A. Seasonal patterns in temperature (degrees C) throughout the water column, as illustrated by monthly YSI temperature profiles.

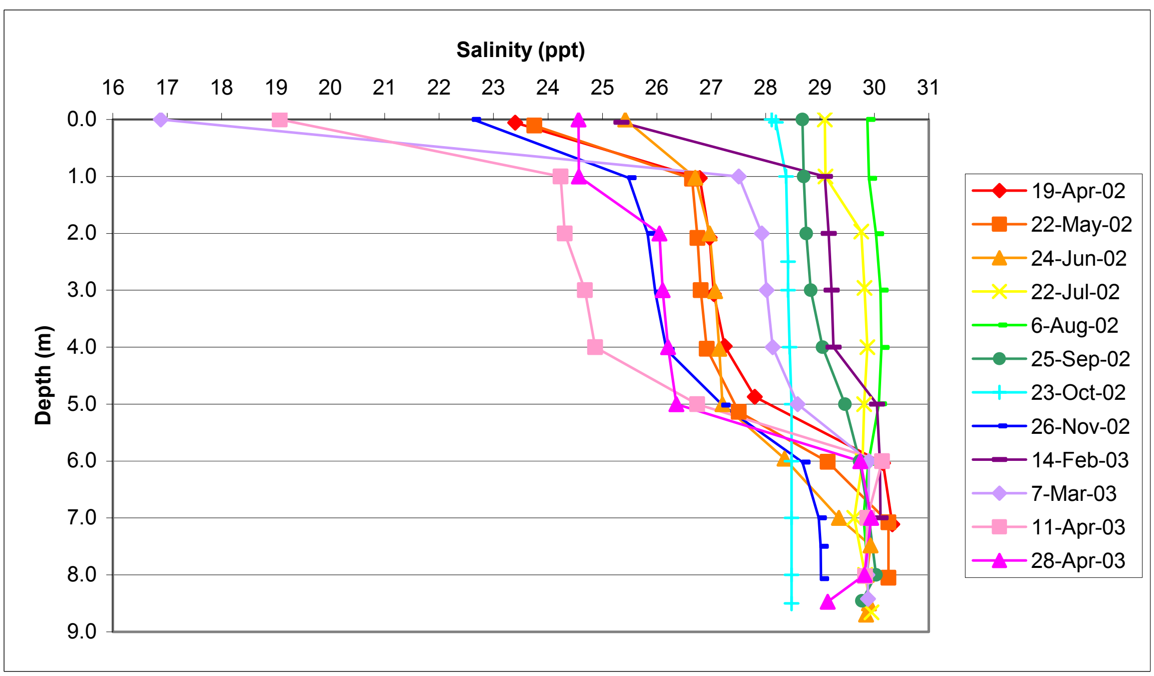


Fig. 2B. Seasonal patterns in salinity (parts per thousand) throughout the water column, as illustrated by monthly YSI salinity profiles.

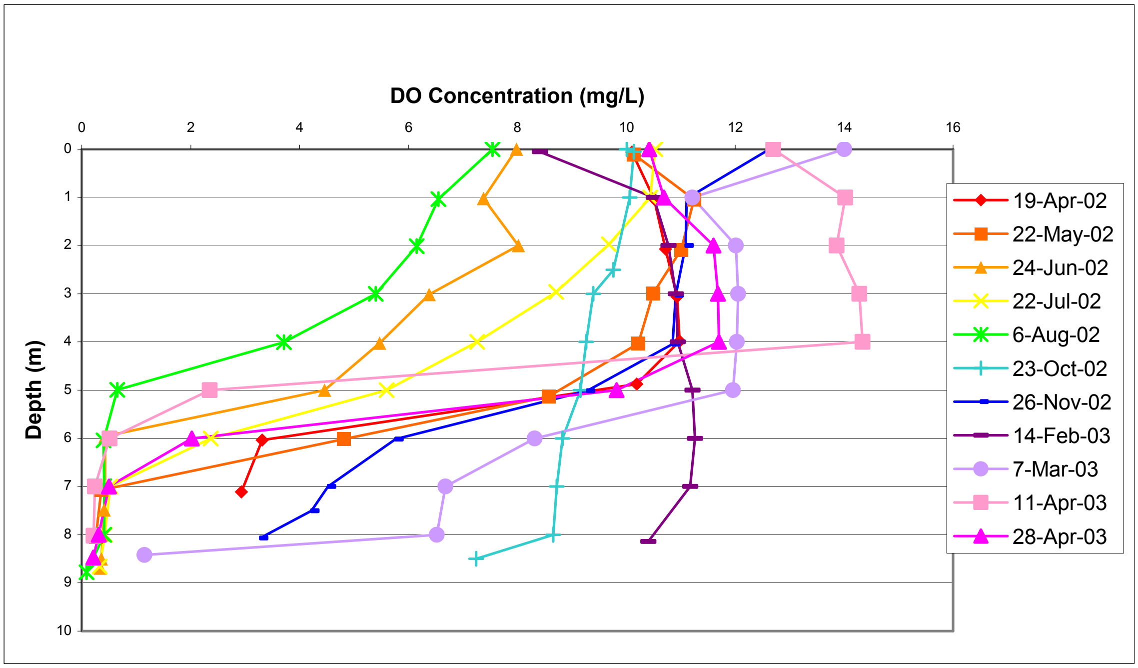


Fig. 2C. Seasonal patterns in dissolved oxygen concentration (mg/L) throughout the water column, as illustrated by monthly YSI DO concentration profiles.

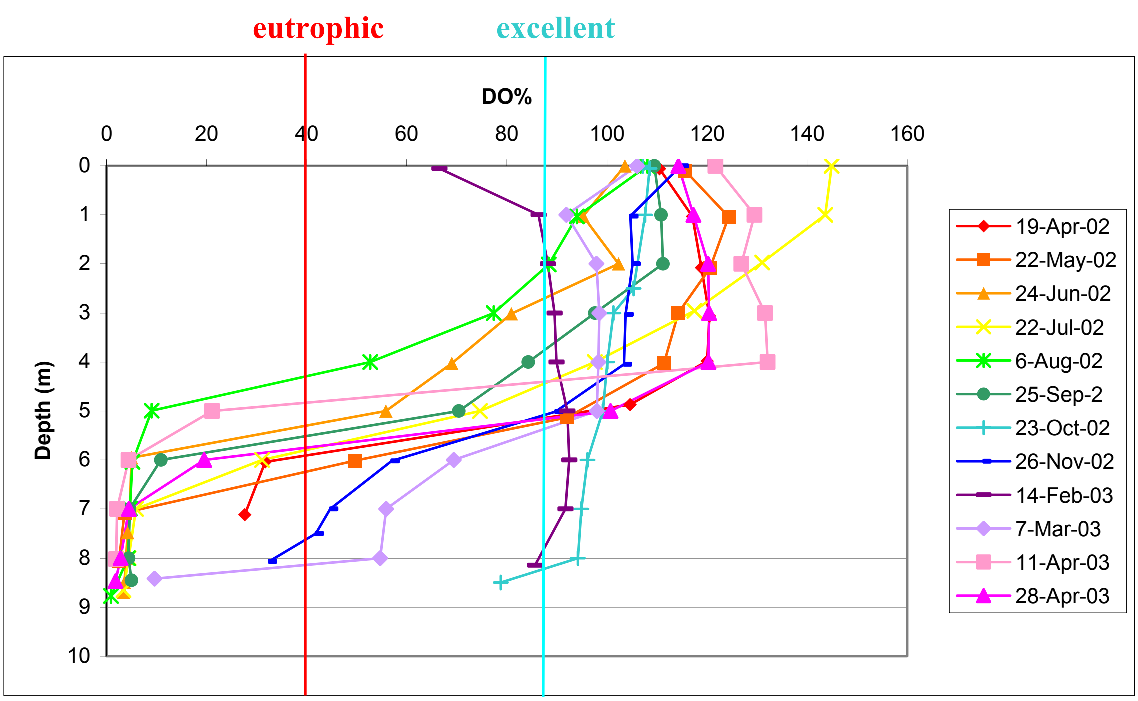


Fig. 2D. Seasonal patterns in percent saturation of dissolved oxygen throughout the water column, as illustrated by monthly YSI DO percent saturation profiles. Lines representing 0 and 100 points on the Buzzards Bay index are marked "eutrophic" (40%) and "excellent" (90%). Note: the Maine DEP requirement for DO percent saturation is 85%.

Figures 3A-3C: Ocean Data View Profiles

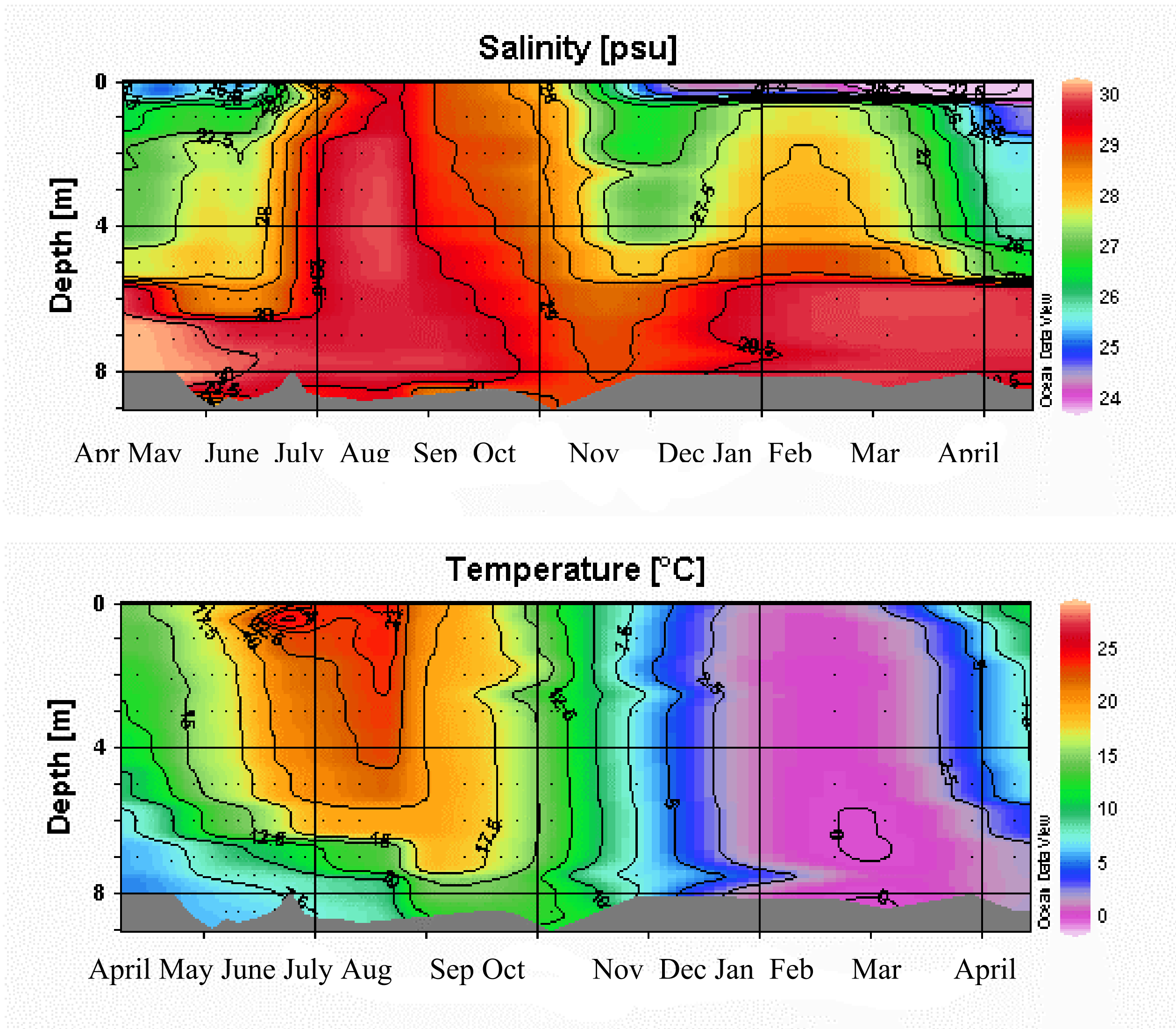


Fig. 3A. Ocean Data View color mapping of YSI temperature and salinity profiles for all sampling dates from April 2002 to April 2003. Lowest levels indicated by purple, highest by red. Gradients in color from surface to bottom at a given time of year indicate presence of halocline or thermocline. Areas of solid color indicate homogenous water column.

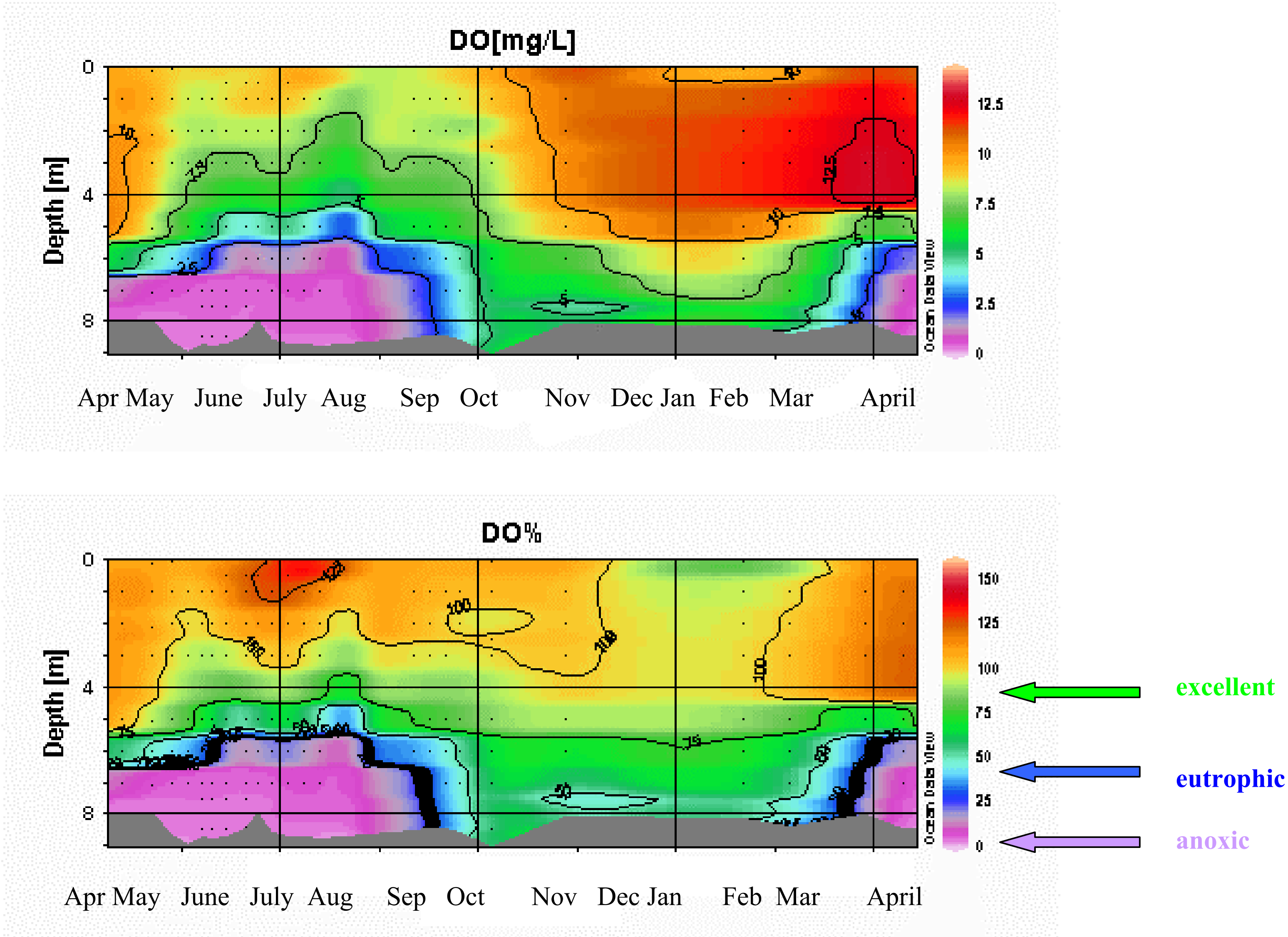


Fig. 3B. Ocean Data View color mapping of YSI DO concentration and percent saturation profiles for all sampling dates from April 2002 to April 2003. For percent saturation, light green indicates excellent levels, blue indicates highly eutrophic levels, and light purple indicates nearly anoxic levels (eutrophic and excellent definitions from Buzzards Bay Health Index).

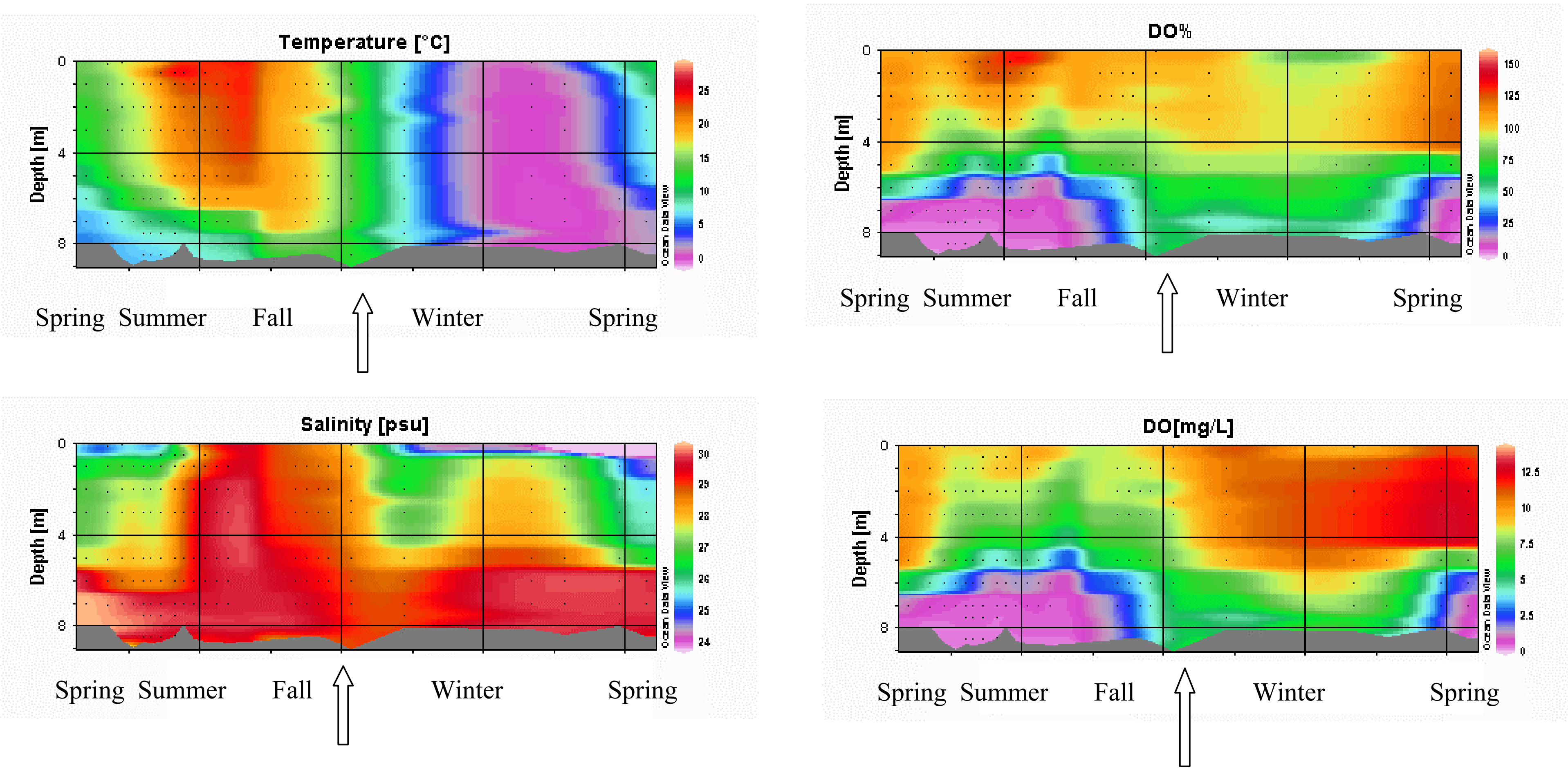


Fig. 3C. All Ocean Data View profiles, with seasons demarcated. Trends across all profiles can be observed.
Periods of stratification across all four parameters: Spring '02, early Summer, Spring '03.
Periods of relative homogeneity across all four parameters: last point in fall (see arrows), winter (with the exception of low-salinity ice cover, indicated by purple at surface).

Figures 4A –4E: Continuous Surface Data for August-September, 2002.

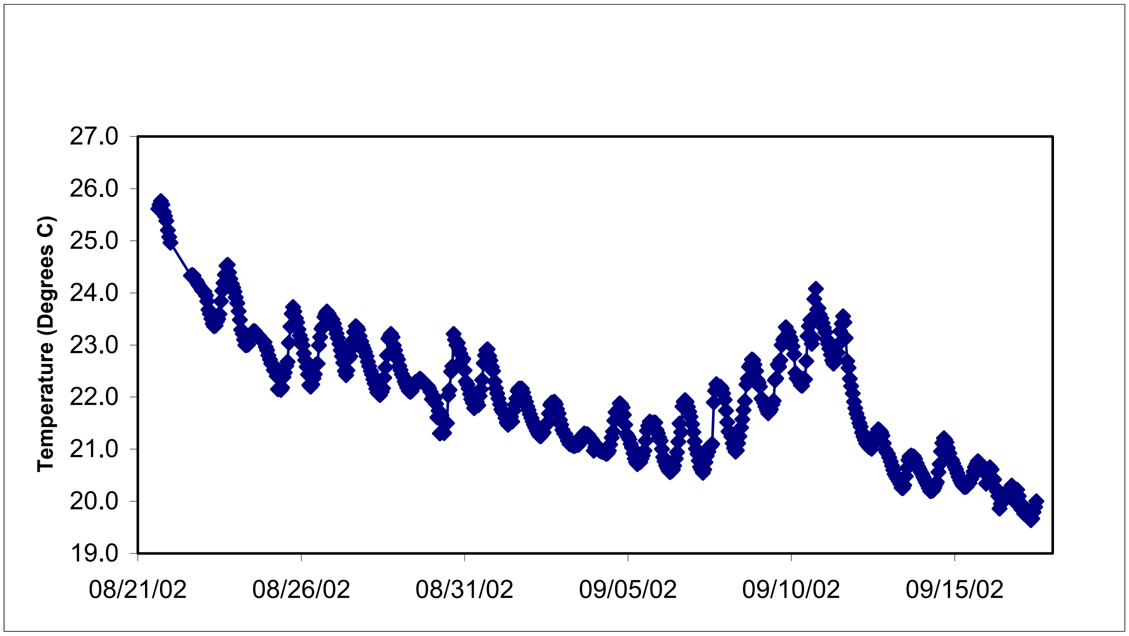


Fig. 4A. Continuous temperature data recorded in surface water above the deep hole by YSI from August to September 2002.

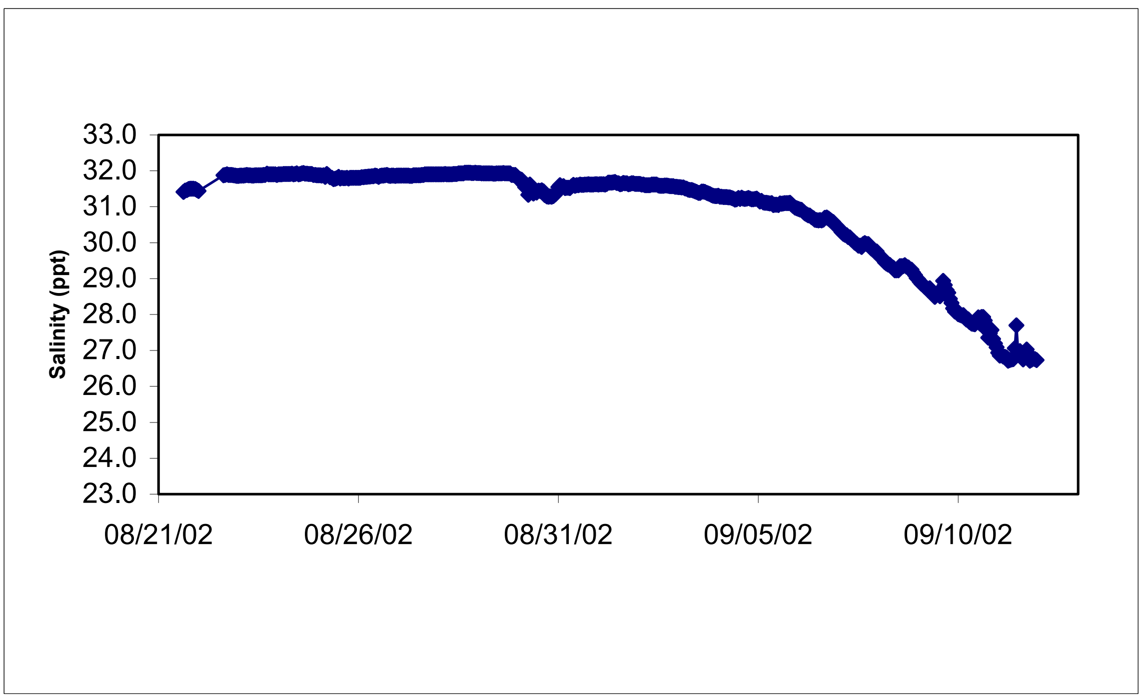


Fig. 4B. Continuous surface salinity data recorded in surface water above the deep hole by YSI from August to September 2002.

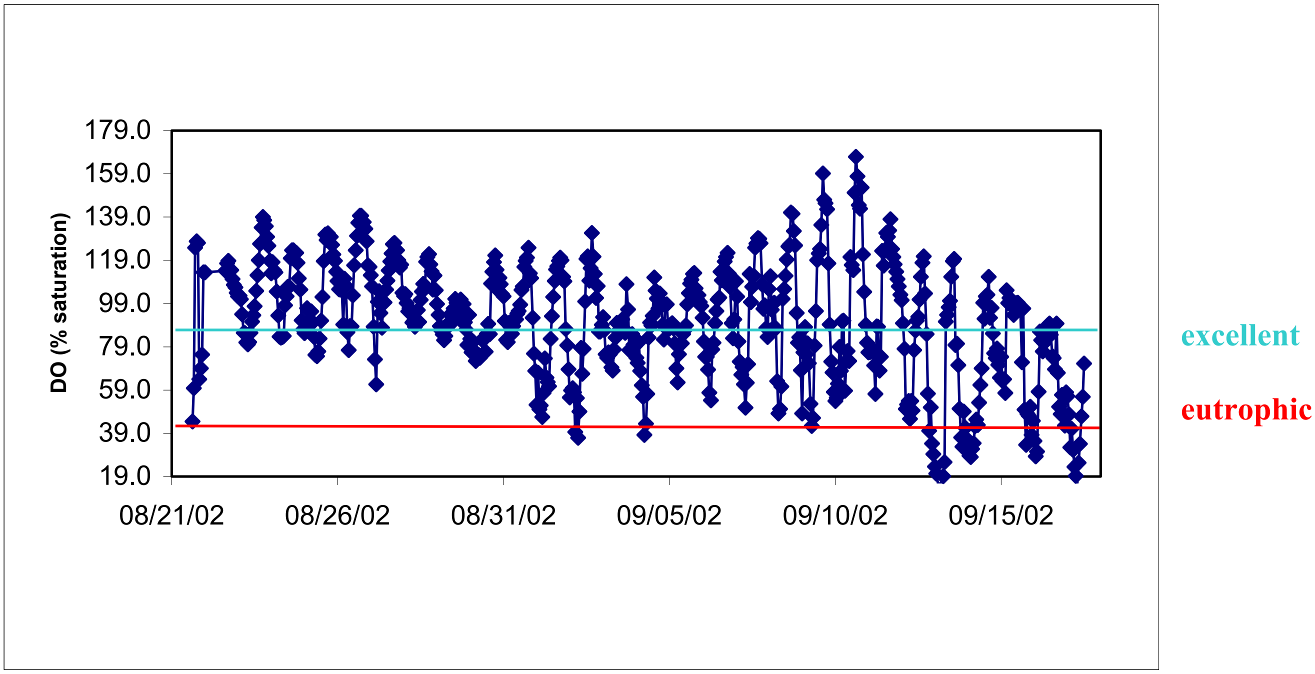


Fig. 4C. Continuous dissolved oxygen percent saturation data recorded in surface water above deep hole by YSI from August to September 2002. Excellent and eutrophic levels (90 and 40% saturation) based on Buzzards Bay Health Index.

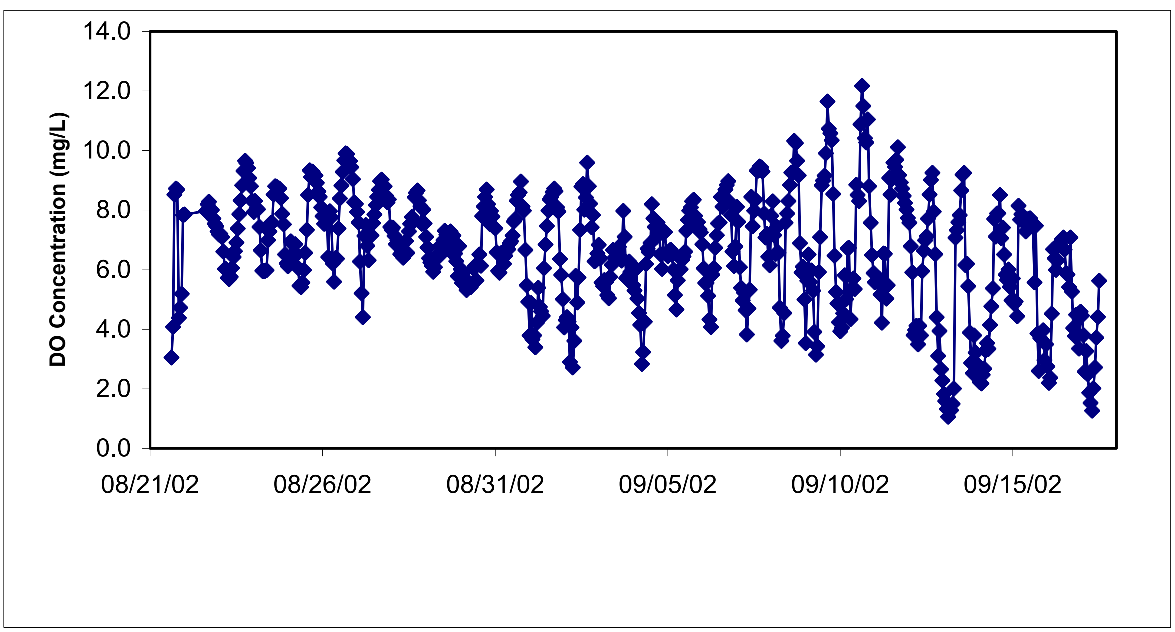


Fig. 4D. Continuous dissolved oxygen concentration data recorded in surface water above deep hole by YSI from August to September 2002.

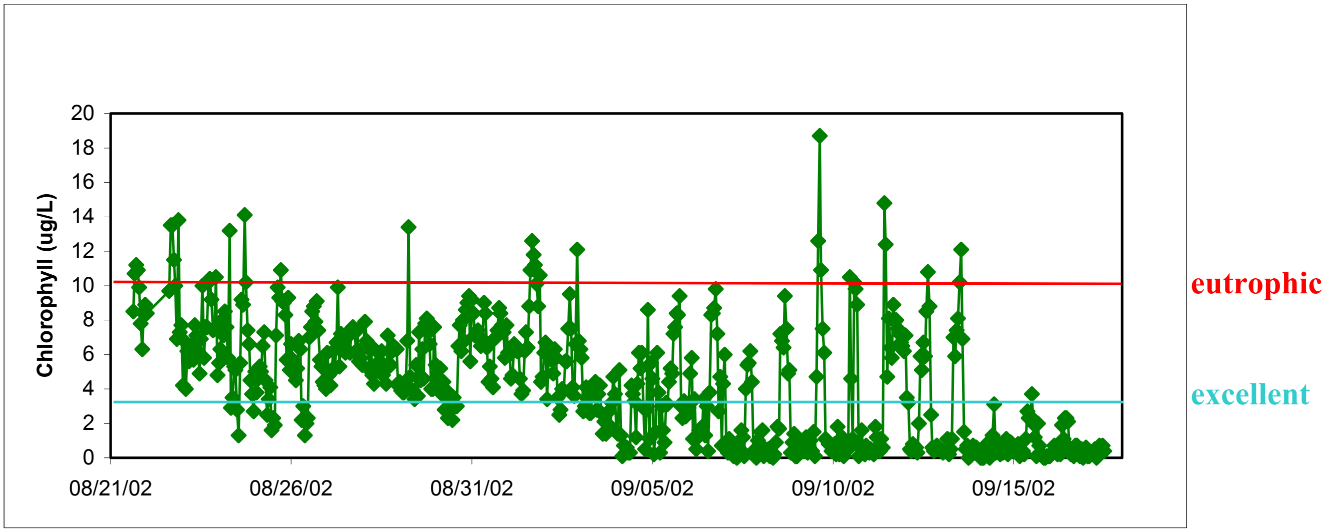


Fig. 4E. Continuous surface chlorophyll a (combined chlorophyll and phaeophytin) data recorded in surface water above deep hole by YSI from August to September 2002. Excellent and eutrophic levels (3 and 10 ug/L) based on Buzzards Bay Health Index.

Figure 5A-5B: Continuous Temperature Profiles, 2/03-4/03

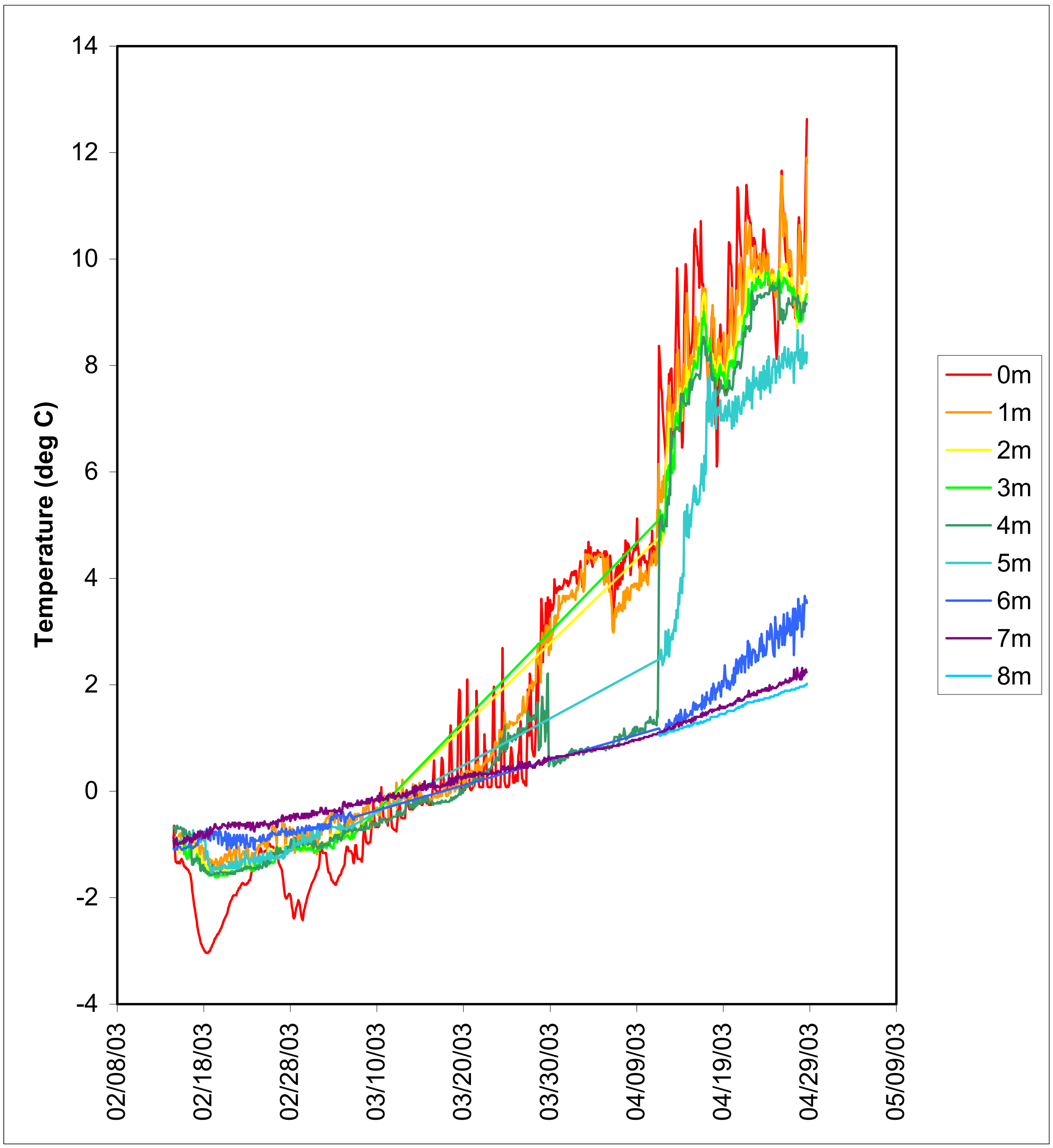
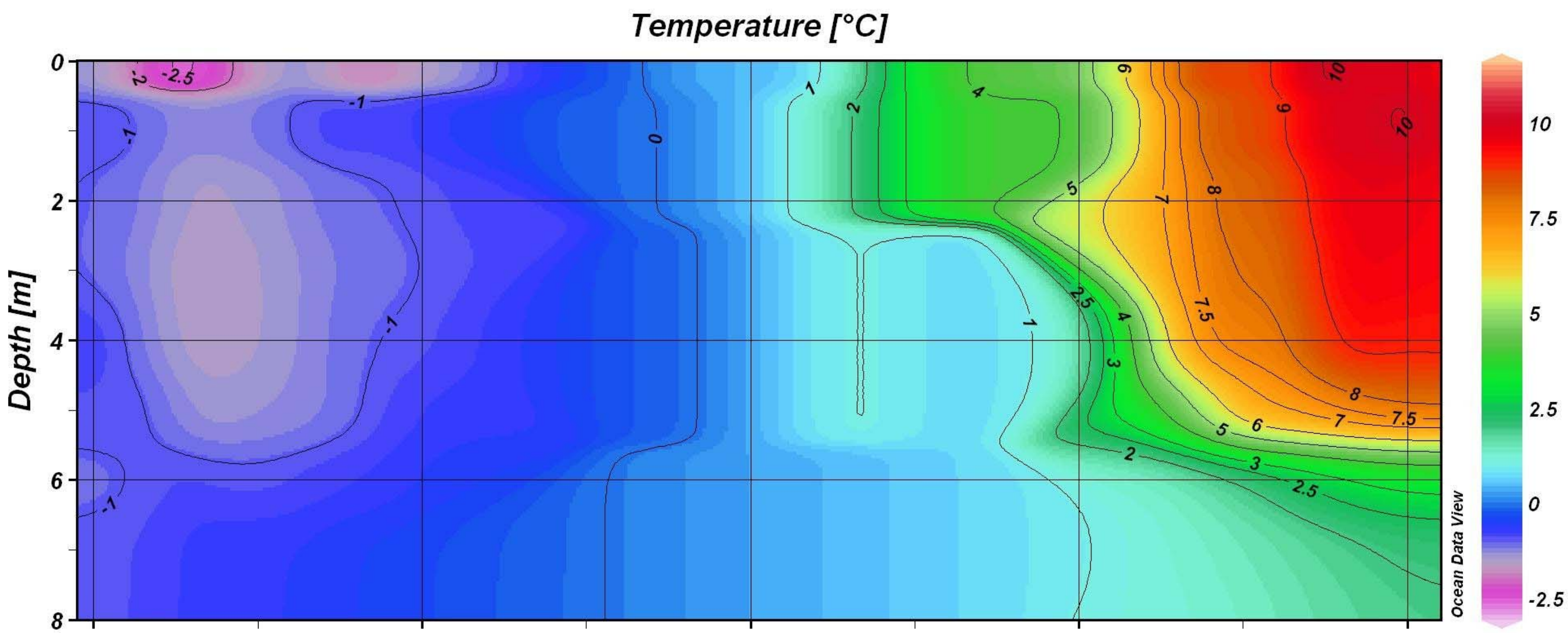


Fig. 5A. Continuous water column temperature profiles recorded from February 14 through April 28, 2003 using digital temperature probes moored at the deep hole at defined intervals. Several probes were removed on March 7 and replaced on April 11, which is why some of the lines appear straight for period of time.



Feb14 Mar1 Mar15 Apr1 Apr15 Apr 28

Fig. 5B. Ocean Data View graph of continuous water column temperature profiles recorded from February 14 through April 11, 2003 with digital temperature probes moored at the deep hole. Purple at surface from February14 through March 1 indicates extremely low temperatures due to the 2ft. of ice cover. Ice cover gone by mid March. Stratification begins April 1.

Figures 6A-6E: Nutrient Sample Data

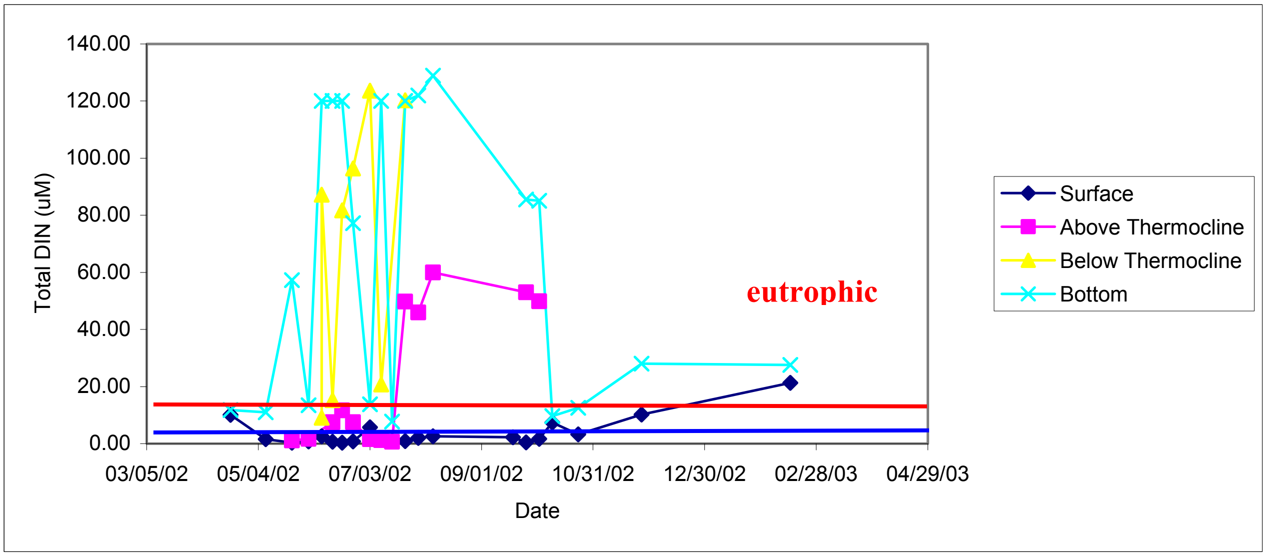


Fig. 6A. Seasonal variations in total dissolved inorganic nitrogen (DIN) throughout the water column (in uM). Total DIN calculated as combined ammonium, nitrate, and nitrite. Level above 10 uM eutrophic, according to Buzzards Bay Health Index.

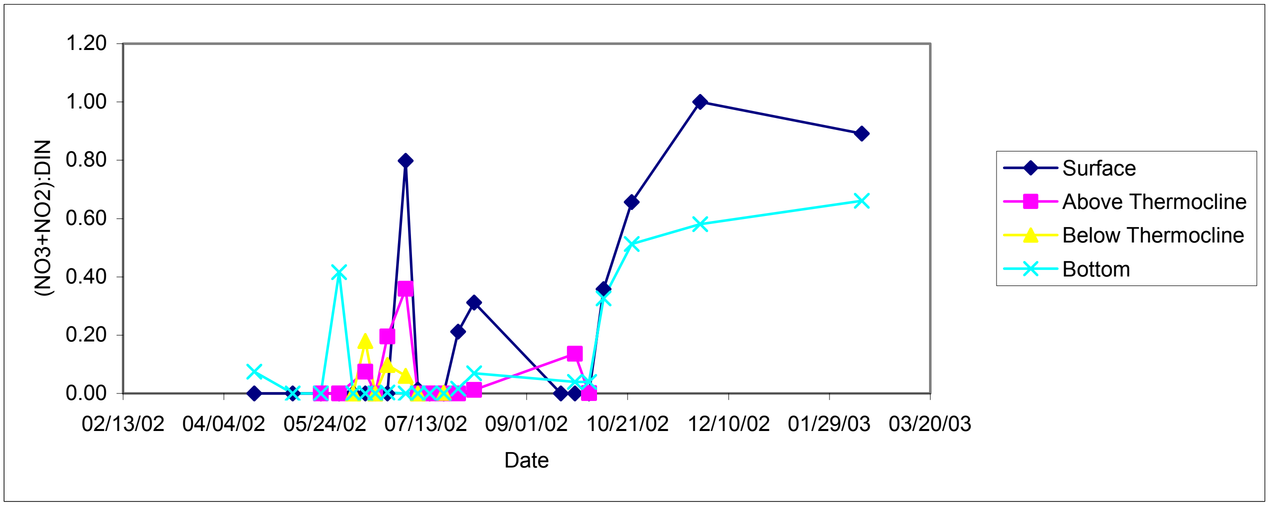


Fig. 6B. Seasonal variations in ratio of combined nitrate (NO3) and nitrite (NO2) to total DIN throughout the water column.

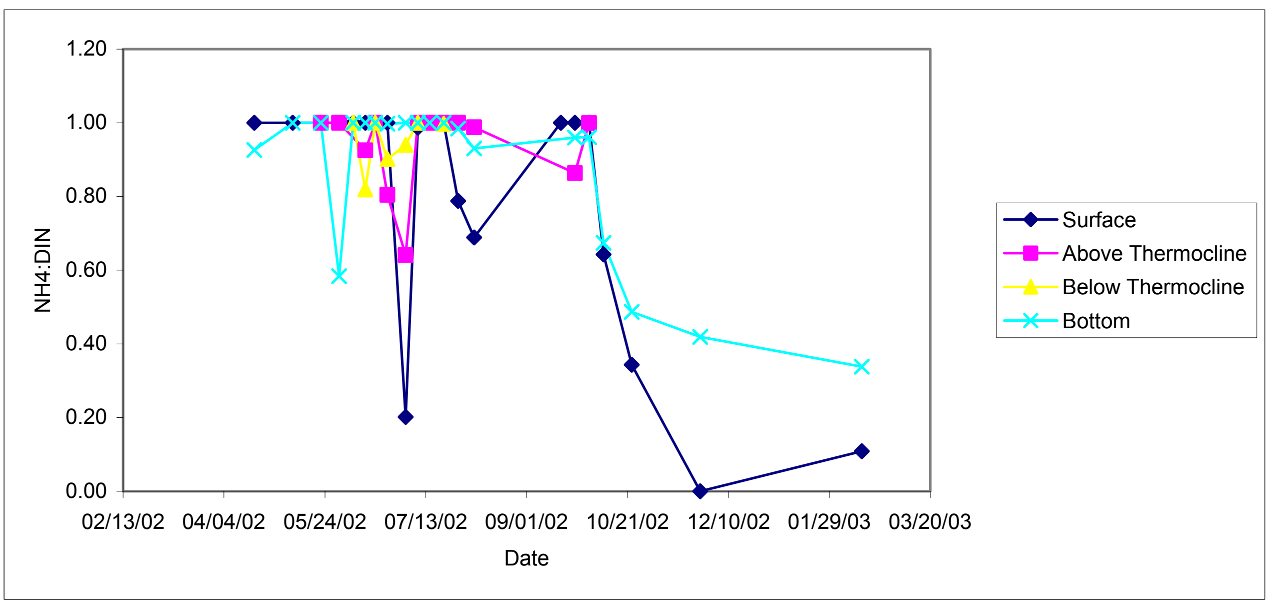


Fig. 6C. Seasonal variations in ratio of ammonium (NH4+) to total DIN throughout the water column

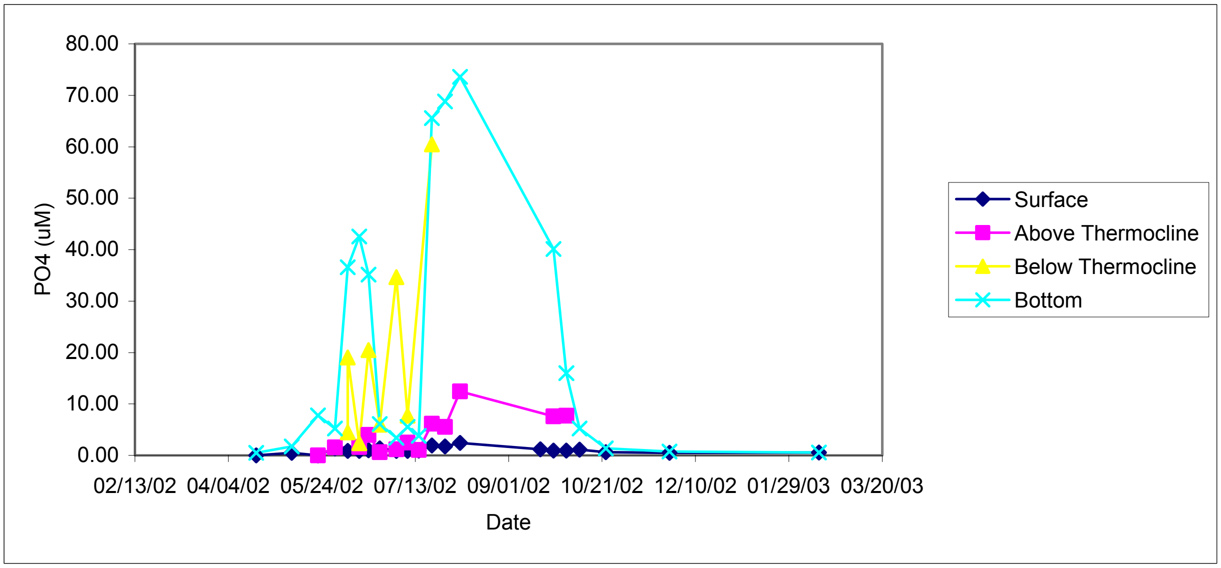


Fig. 6D. Seasonal variations in phosphorous (PO4) levels throughout the water column (in uM).

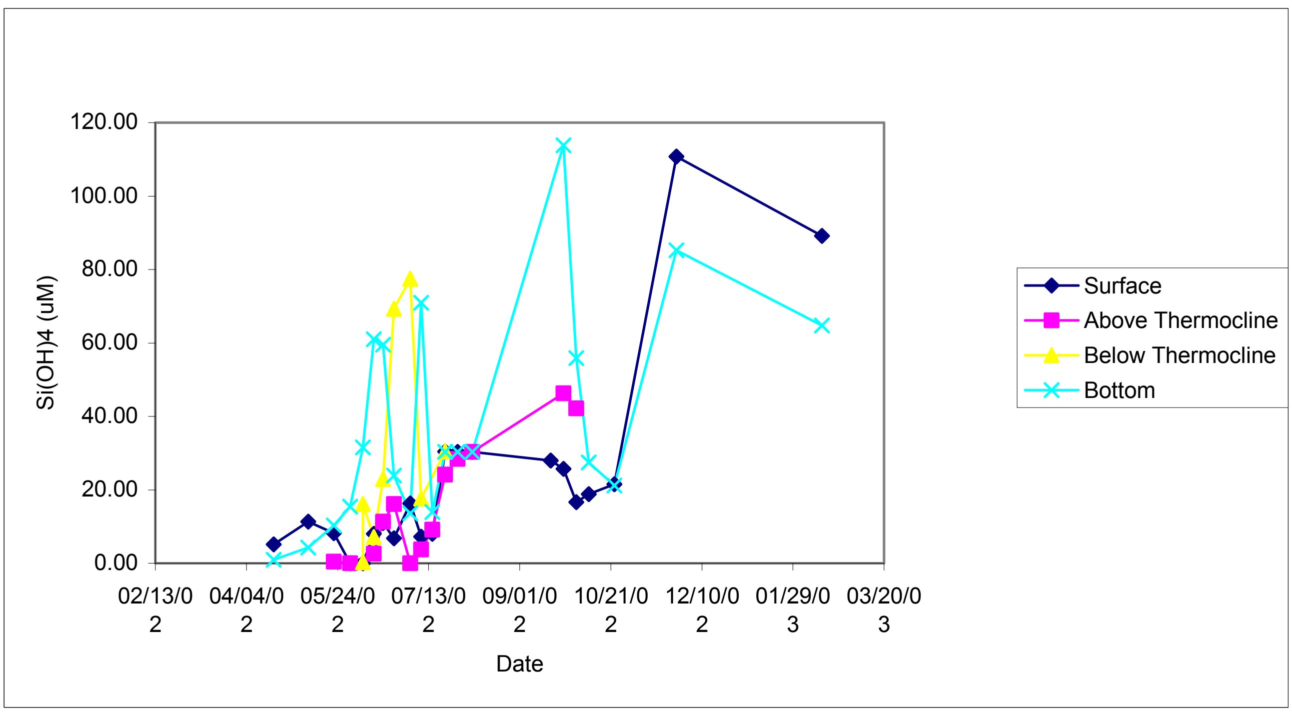


Fig. 6E. Seasonal variations in silicate (Si(OH)4) levels throughout the water column (in uM).

Figures 7A-7B: Chlorophyll and Phaeophytin Sample Data

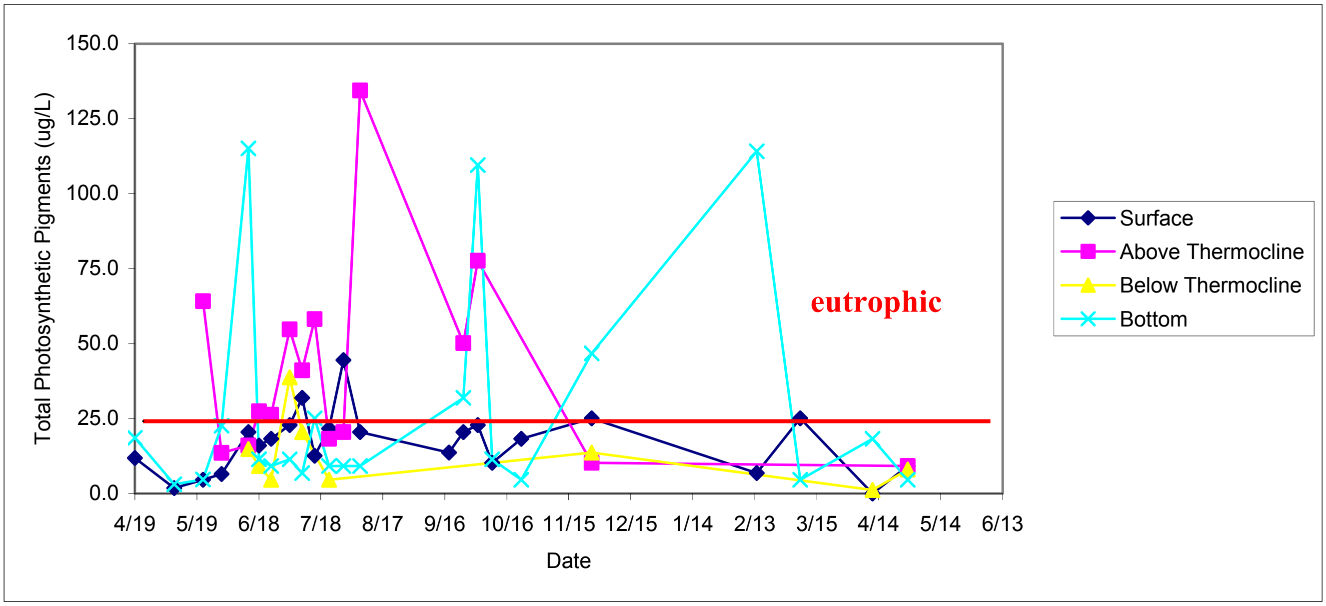


Fig. 7A. Monthly variations in total photosynthetic pigment levels (combined chlorophyll-A and phaeophytin) throughout the water column. Levels of 10 ug/L are extremely eutrophic according to Buzzards Bay Health Index.

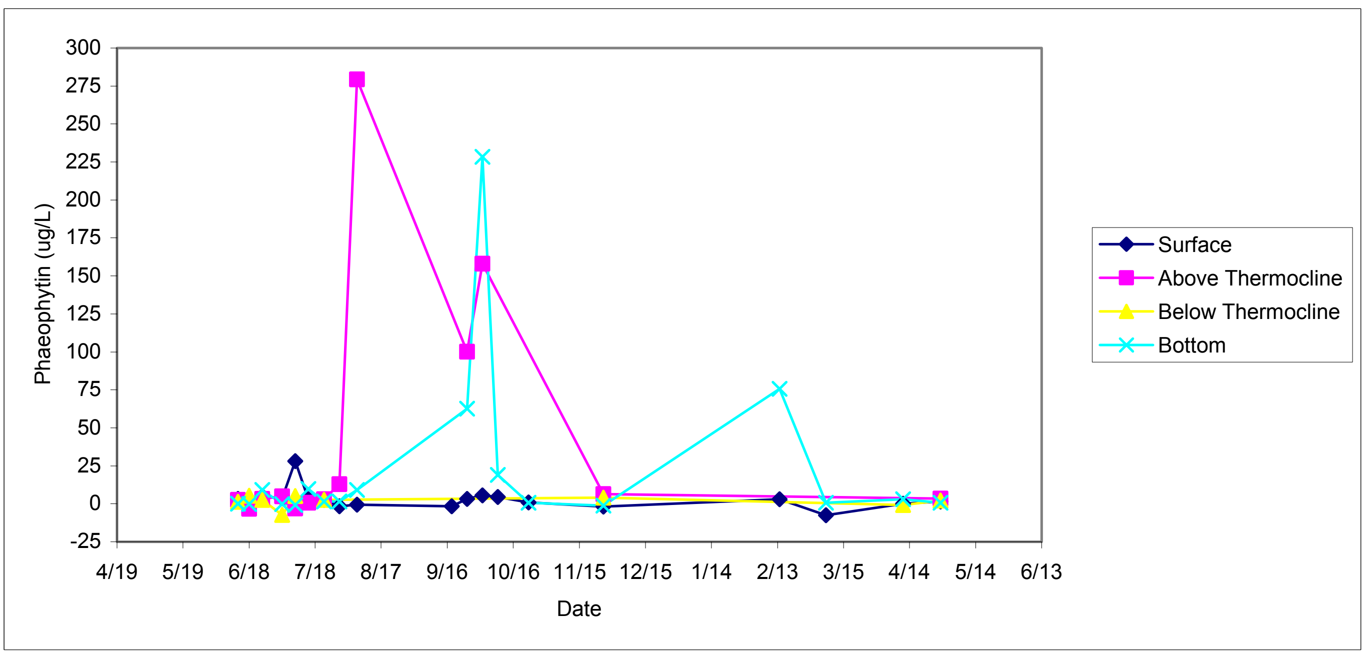


Fig. 7B. Monthly variations in phaeophytin levels throughout the water column.
Low proportion of phaeophytin to total photosynthetic pigments indicates growth.
High proportion of phaeophytin to total photosynthetic pigments indicates decline.

Figure 8: Secchi Depths

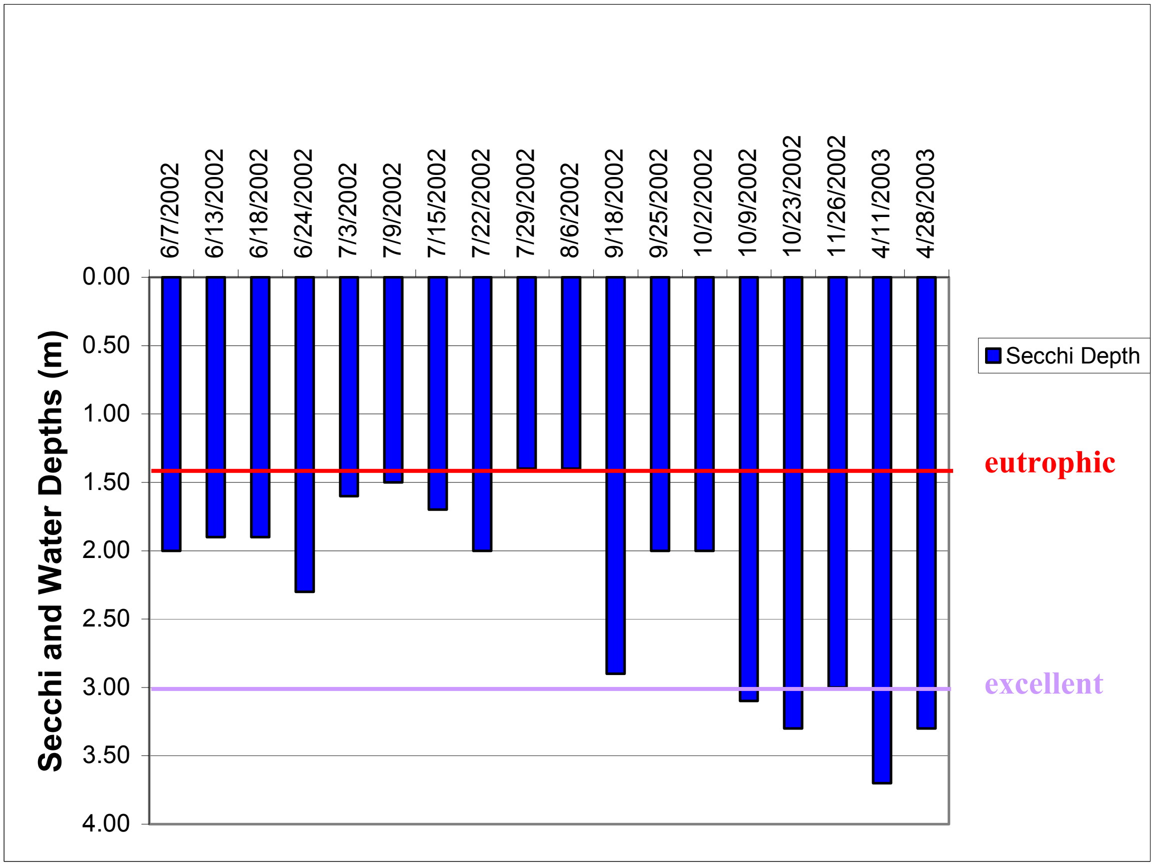


Fig. 8. Seasonal variations in water turbidity as measured by secchi disk depth. Secchi depth data for spring 2002 was not available. Depths from 0.6 to 1.4m are eutrophic and depths above 3m are excellent according to Buzzards Bay Health Index.

Figures 9A-9C: Yearly Weather Patterns for Brunswick
(All data for graphs obtained from: http://www.erh.noaa.gov/er/car/climate.htm, accessed April, 2003.)

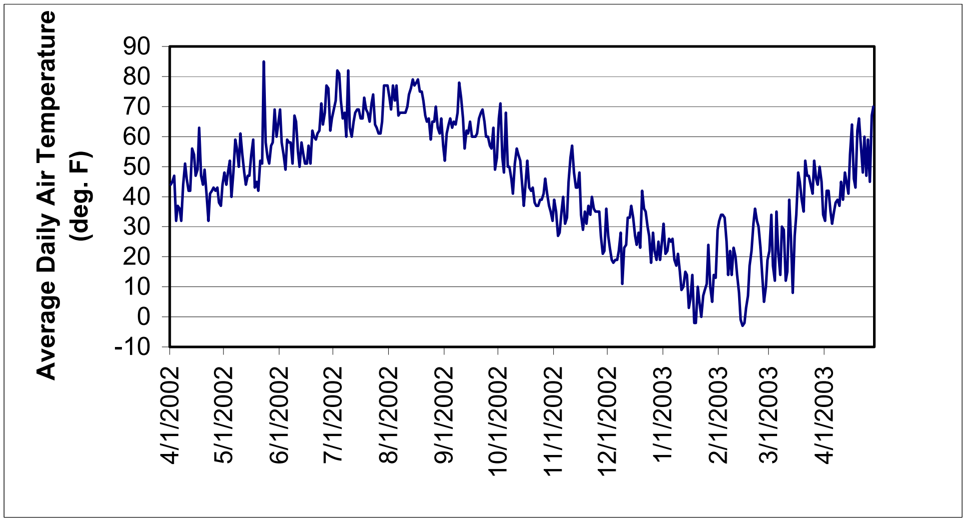


Fig. 9A. Variations in average daily temperature in Brunswick, ME from April '02 through April '03.

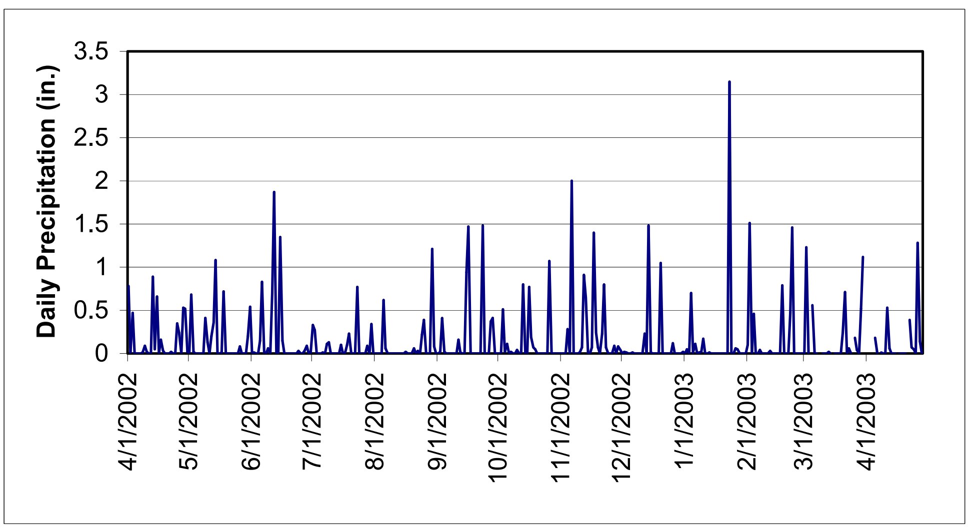


Fig. 9B. Variations in total precipitation measured over a 24-hour period in Brunswick, ME from April '02 – April '03.

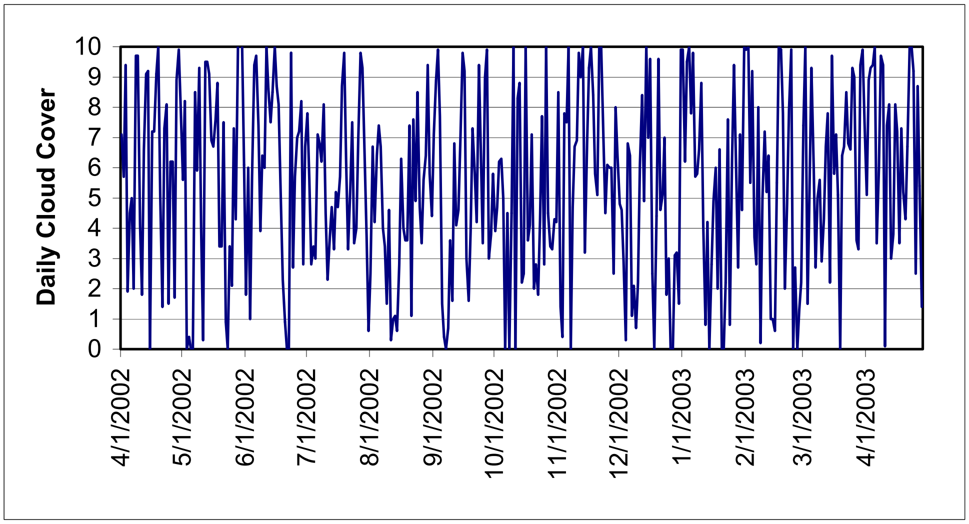


Fig. 9C. Variations in cloud cover in Brunswick, ME: April '02 – April '03. The Y axis represents cloud cover in tenths, with 10.0 representing a day of total cloud cover and 0.0 representing a nearly clear day.

DISCUSSION

Introduction

One of the main goals of this study was to assess the water quality at the deep hole of the Lower Lake based on the parameters measured, which necessitated an index that rated specific measurements of relevant parameters in terms of water quality. The Buzzards Bay Health Index (Table 1) was referred to frequently, as this was the only available index based on a New England estuarine environment (Howes, 2002). The index, created by the Coalition for Buzzards Bay, provides standards for four basic parameters--DO percent saturation, secchi depth, chlorophyll-a levels, and total dissolved inorganic nitrogen (DIN)—and uses a point system to rate assign given levels as indicators of various categories of water quality. The point system corresponds to the most healthy and least healthy environments observed at the Buzzards Bay estuary. Lines corresponding to this point system were drawn on all of the relevant graphs.

Table 1: Buzzards Bay Health Index

Good-Excellent: 65-100
Fair:35-65
Poor/Eutrophic: <35

	0 points	100points
DO% Sat.:	40	90
Secchi Depth (m):	0.6	3
Chl-A (ug/L):	10	3
DIN (uM/L):	10	1

(Howes, 2002)

The Buzzard's Bay Index provided a useful point of reference, putting the water quality indicators observed throughout the year at the deep hole into perspective. In general, the parameters at the lower lake exhibited poor or eutrophic conditions often for several periods over the year; however, many cases, the detrimental levels of DO, chlorophyll, and DIN exceeded the poorest levels specified by the Index by an entire order of magnitude. This was true for all three of these parameters throughout most of the summer toward the bottom of the water column. Eutrophic conditions were evident throughout the majority of the year. However, seasonal factors such as heavy rainfall and low temperatures counteracted these effects for certain periods out of the year by encouraging vertical mixing. Numerous factors were important in determining the presence and extent of eutrophic conditions in the deep hole region of the Lower Lake.

Salinity patterns were central to analyzing eutrophication patterns in the Lower Lake in several important respects. These patterns are summarized by Lowery (1998) in his report on modeling estuarine eutrophication. First, as Lowery stated, patterns of salinity indicate the amount of freshwater input to the estuary, which can also signify nutrient loading. Thus, he specifies an inverse relationship between nutrients and salinity, which translates to a similar relationship between salinity and phytoplankton production governed by those nutrient levels. A similar correlation between low salinity, high nutrients, and high chlorophyll-A levels (indicative of phytoplankton production) was found by Litaker et. al. in their 1987 study. Indeed, patterns throughout the year indicated that these relationships generally held true for the New Meadows site. A freshwater lens was present on the surface of the water column for most of the year, during the same times that extremely elevated nutrient and chlorophyll levels were also present. The frequent correlation of high precipitation with elevated nutrient levels enforces the likelihood of such an effect, also bringing into play seasonal patterns in precipitation.

Lowery (1998) also points to the importance of water column stratification of salinity and or temperature in potentially isolating hypoxic bottom waters, augmenting the effects of eutrophication. In their study of the Delaware and Mobile Bay estuaries, Pennock et. al. (1994) found that salinity stratification and the resulting lack of mixing within the water column was a primary factor making estuaries more susceptible to eutrophication. This finding is especially relevant in the case of the Lower Lake, because intense salinity stratification with the aforementioned freshwater lens was evident in the YSI profiles throughout much of the year. In addition, in spring and fall, DO patterns within the water column tended to follow patterns in salinity, with an inverse relationship between the two parameters. However, during certain periods, temperature stratification appeared to be more important than salinity in augmenting the effects of eutrophication. During the summer, when bottom DO levels and general water quality parameters were at their poorest, a pronounced thermocline was present, while salinity was quite homogenous. This points to the case that patterns of both salinity and temperature stratification are central in governing the expression of eutrophication in this system, but that seasonal effects cause one parameter to take precedence over the other.

Nitrogen loading from external sources appeared to play a significant role in triggering algal blooms in the spring, summer, and fall. In accordance with definitions of the *f*-ratio, the DIN was composed of nitrate and nitrite. These forms of nitrogen were generally more important than ammonium for the seasonal blooms. However, ammonium was also important in maintaining high algal biomass. Heinig (2002) reported that the deep hole of might be a source of nutrient regeneration in the Lower

Lake. Indeed, the frequent high ammonium levels observed over the summer support this observation.

The following discussion focuses on the water quality patterns and eutrophic conditions observed during each season over the course of the year. Seasonal periods are defined as mid winter through spring (February through May), late spring through summer (June through August), and end of summer through late fall (September through November). Seasonal effects and variations--the overall patterns in stratification, nutrient loading, algal biomass, and weather patterns—are first discussed, followed by an evaluation of water quality indicators based on the Buzzards Bay Health Index.

Mid Winter-Spring

Seasonal Effects and Variations

The winter sampling data indicate little or no stratification in the water column. As the temperature data show, the water was cold and well-mixed, as one would expect during the winter months. The thick ice cover present from February 14 through March 7, 2003 undoubtedly resulted in the low surface salinity observed during this time. The highest precipitation of the year (over 3in.) that preceded the February sampling date may have also contributed to this effect. Similarly, ice and precipitation most likely contributed to the extremely low surface salinities (the lowest of the year) in March and April, 2003 and presence of a pronounced halocline. A period of low precipitation in the middle of February had been followed by several weeks of heavy precipitation that lasted until the time of the March sampling.

An early spring phytoplankton bloom at the Lower Lake took place from March to April, 2003. High total pigment levels and a low proportion of phaeophytin during this period indicate rapid growth. The low-salinity lens had the lowest measured salinity of the year, and DO patterns followed patterns of salinity stratification very closely. There was also a pattern of elevated DO levels in the mid-portion of the column, which then became severely depleted lower down, indicating high algal production in the middle part of the column and high benthic decomposition at the bottom of the hole. However, nutrient samples will need to be analyzed in order to build up a clearer picture of the causes and effects of the bloom. It is likely that seasonal changes including precipitation, cloud cover and temperature were all important in creating the right conditions for this bloom: average daily air temperature rose from 15 to 50 degrees F from March to April, 2003. A period of high precipitation in early March was followed by a period of incomplete cloud cover throughout much of the month. Thus, it is possible that mid March was a time of high light intensity, contributing to phytoplankton growth and production. This effect was combined with very low turbidity of the water column, creating optimal conditions for a bloom. However, the question remains whether nutrient loading from outside sources actually triggered the bloom.

According to the results, it appears that the period of spring following the early spring bloom can be regarded as a transitional period for the pattern of water column temperature stratification coupled with low DO levels, which greatly intensifies in the summer. This is supported by the data from the continuous temperature profile taken from February through April, 2003, which shows a transition in stratification around the beginning of April, when surface temperature levels began to rise much more quickly than the lower portion of the column. Patterns in water circulation, coupled with the seasonal increase in light intensity may have contributed to this effect. Following this pattern with the 2002 data, temperature stratification began to intensify gradually from April to May 2002, while salinity stratification with low surface levels continued through June. This stratification was accompanied by low bottom DO levels. Temperature stratification began in April, while DO depletion began as early as March. It is apparent from the Ocean Data View salinity graph that a low-salinity lens was present during the entire period from winter through spring. The low-salinity lens and relatively frequent rainfall might be expected to correlate with increased the nitrates and nitrites associated with nitrogen loading from outside sources (Gilpin, 2000). Indeed, a large amount of nitrogen loading apparently occurred earlier in the season. Nutrient levels in February were notably elevated, with the DIN composed almost entirely of nitrate and nitrite at the surface.

In May, the nutrient patterns changed. The large increase in nutrients at the bottom was due almost entirely to ammonium, which is associated with internal regeneration through trophic processes, rather than outside sources (Pinckney et. al., 2001) The chlorophyll data and low phaeophytin levels together indicate a period of significant algal growth at the surface. The relationship of algal growth to weather data is inconclusive, since a short period of very high cloud cover was followed by a low point in phaeophytin around the time of the sampling.

Water Quality Indicators

The winter-spring period illustrates the influence of temperature and salinity stratification on eutrophication in the Lower Lake. DO stratification followed patterns of salinity stratification quite closely during this entire period. DO was unstratified in February and consistently high, unsurprising given that the cold water was dissolving high amounts of oxygen and the column was well-mixed. February saw high DO levels around 10mg/L and 100%, well above the optimal range specified by the Buzzards Bay Health Index, given around 90% (Howes, 2002). The surface readings, however, were lower than the rest of the column, a phenomenon which may have been influenced by tidal cycles, ice cover, and water flow throughout the column. The capacity of cold winter water to dissolve oxygen and maintain homogeneity prevented eutrophic conditions during this month, with salinity and DO being well-mixed throughout the column in the absence of a thermocline. DO patterns for March were strikingly different, with remarkably *high* DO levels at the surface, and hypoxic levels at the bottom (less than 1 mg/L or 10%, well below the 40% cutoff specified by the Health Index). DO was stratified throughout the water column, but maintained acceptable levels above the bottom reading (Howes, 2002). March was also the time when the lowest –salinity lens was present (only 17 ppt), pointing to the importance of salinity in affecting DO patterns. The significant spike in chlorophyll-a levels at the surface point to the presence of a large, early-spring algal bloom, which was most likely responsible for the elevated DO levels in the upper part of the water column.

In April, 2003, DO was highly elevated—around 14mg/L and above 120% saturation— from 1 to 4m. The drop-off in DO occurred at the same point (4m) where a pronounced halocline and thermocline also began, indicating that both temperature and salinity played an important role. Although the salinity and DO stratification were not quite as significant in April 2002, they generally follow the same pattern of correlating stratification by salinity, temperature, and DO. In all cases, bottom levels were badly depleted of oxygen, although not with the same severity as occurred in the summer months. There was also a transition in the phytoplankton population from the middle to the end of April. Unusually high chlorophyll-a levels at the bottom, indicating growth, apparently became mixed throughout the water column toward the end of April.

In April and May, 2002, bottom DO was still at hypoxic levels (less than 40%), likely as a result of the early spring bloom. Kristiansen, et. al. (2001), who studied the early spring algal bloom in Norway's Oslofjord, determined that nitrate and silicic acid were the primary limiting nutrients whose depletion caused the collapse of the bloom. Of the two nutrients, they found nitrate to be the more important, since silicic acid was depleted first. Kristiansen et. al. (2001) used a proxy of the *f*-ratio—the ratio of nitrate to ammonium—as a measure of new versus regenerated nitrogen production, finding that the ratio varied depending on the stage of the bloom. They found a shift from nitrate (new production) to ammonium (regenerated production) as the primary source of growth, with *f*-ratio values going from above 0.9 to between 0.5 and 0.7. This shift coincided with a decline in the phytoplankton population.

It is interesting to compare the pattern observed in the Krisiansen et. al. (2001) study with the spring bloom at the Lower Lake, for it appears that nutrients indeed followed a similar trend. Surface chlorophyll-a levels tripled from March to February 2003, with low phaeophytin, so this was a period of rapid growth. Surface and bottom DIN levels were quite high during this time, at above 20uM. Surface levels were composed entirely of nitrate and nitrite in February, with only a slight increase in the proportion of ammonium in March. In April, 2002, chlorophyll levels were high (between 10 and 20ug/L) at both the surface and bottom , although because data was obtained from the YSI sensor, the distinction between growing and declining biomass (as evidenced by the ratio of phaeophytin to chlorophyll-a) cannot be determined. Total chlorophyll levels dropped off in May, however, indicating that a crash was in progress. While nutrient levels in April were low on the scale of the graph, they were still close to the threshold for poor quality conditions specified by the Health Index:10ug/L. The fact that DIN was composed almost entirely of ammonium during this time would indicate that the patterns determined by Kristiansen et. al. (2001) in fact hold true for the Lower Lake.

While cloud cover fluctuated widely and relatively periodically throughout the year, we can see that there was a point of no cloud cover shortly before the April 19 sampling date which may have encouraged photosynthesis in conjunction with the high nutrient levels. The high point of ammonium in May, at 60ug/L, was six times as high as the Health Index threshold (Howes, 2002). The ammonium was probably produced from the waste of protozoa grazing on bacteria (Pinckney et. al., 2001), which could be present in high levels if there had been a large die off of phytoplankton. The decomposition of plankton biomass by these bacteria would be using up oxygen. The chlorophyll-a data seems to support this assumption, as the elevated levels in April, '02, had dropped off by

May. Thus, it is possible the high ammonium was left over from decomposition that had occurred during that period.

Late Spring-Summer

Seasonal Effects and Variations

All of the late spring and summer months were highly thermally stratified, with pronounced thermoclines. This correlated with the seasonal increase in temperature, which created a mass of warm water in upper part of the water column, which in turn created stratification. DO was also highly stratified, indicating that the isolation of hypoxic and anoxic bottom waters was augmenting the effects of eutrophication. August stands out as the period of highest thermal and DO stratification, both of which increased consistently over the summer months. This was also a part of a notable period in terms of weather: July and August, the hottest months of the summer, saw the lowest levels of precipitation of the year and also generally not as wide a range of variation in cloud cover as during other times of the year. The exception was the end of June, when greater rainfall and cloud cover occurred. This could explain the lack of salinity stratification during these months: the lack of rainfall meant that less freshwater was being introduced and surface water was evaporating, so that salinity concentration in the water column increased as stratification decreased. Thus, the column during these months had high salinity throughout. We can see from the graphs that all these trends were augmented from July to August. Thus, thermal stratification was most important during this period in terms of isolating hypoxic and anoxic bottom waters.

There were frequent massive spikes in total dissolved nitrogen levels throughout the late spring and summer, generally occurring at the bottom or below the thermocline. The first spike, in June, was generally due to ammonium, although the initial spike involved an increase in the proportion of nitrates and nitrites. For the rest of July, the nitrogen levels were maintained through high ammonium toward the bottom of the column. This pattern supports Heinig's observation (2002) that the deep hole may be an important source of nutrient regeneration, since ammonium is associated with regenerated nitrogen. The second spike, in the beginning of July, was accompanied by a huge increase in the proportion of nitrates and nitrites at the surface, which may have been added to the system by the heavy rainfall in June. As in June, the compounds making up the high nitrogen levels were later replaced by high ammonium levels toward the bottom of the column. The spikes in nutrients generally involved accompanying spikes in algal growth above the thermocline and, to a lesser degree, at the surface.

Water Quality Indicators

The late spring and summer months saw extremely hypoxic or even anoxic bottom waters in the deep hole, coinciding with high stratification of both temperature and DO (the Ocean Data View graphs illustrate this particularly well). Below 6.0m, DO levels were 1.0ug/L and 10%, extremely poor. In August, conditions of near total anoxia were approached at the very bottom. As stated before, these poor conditions were undoubtedly augmented by thermal stratification. Another indicator of eutrophic conditions was the high levels of turbidity at the end of July and in August (yearly highs) evidenced by secchi readings of less than 1.5m—just at the threshold for the poor water quality range, according to the Health Index. This high turbidity could have prevented algae from photosynthesizing lower down in the water column, decreasing the euphotic zone, and therefore minimizing the amount of DO in the water column. The chlorophyll and phaeophytin data indicates that phytoplankton growth was limited to the surface. Chlorophyll-a predominated at the surface, while phaeophytin predominated above the thermocline.

These highly eutrophic conditions during the summer were clearly influenced by both nitrogen regeneration and input. The two increases in the proportion of nitrates and nitrites in June and July may have been more important than the high ammonium levels in causing algal blooms, since these forms are more readily taken up by phytoplankton (Garrison, 2002). The chlorophyll levels were quite high during these times—as much as six times the Health Index's lowest registered quality levels (60.0ug/L). In August, the chlorophyll-a levels rocketed up to nearly 140ug/L, with the phaeophytin levels equally high. This signifies a massive die off, coinciding with the extremely hypoxic conditions. Nutrients were also at their highest levels of their year at the bottom and above the thermocline, still with ammonia being the primary component. Again, this most likely signifies high levels of decomposition and regeneration.

End of Summer to Late Fall

Seasonal Effects and Variations

The continuous surface data shows surface chlorophyll and DO fluctuating rapidly between excellent and highly eutrophic levels. One might expect the continuous DO and chlorophyll-a data to illustrate daily light/dark cycles of phytoplankton production, with the low points generally falling near dawn; however, patterns between time of day and levels of DO and chlorophyll are difficult to detect. The ranges fluctuated most drastically between day and night towards the end of August and the low points were consistently at zero during September; however, the highest points of chlorophyll levels also occurred at this time—well above 10 ug/L, the highest levels specified by the Health Index. However, points above 10 ug/L occurred throughout the sampling period, indicating a bloom in progress that was perhaps reaching its maximum around the middle of September and preparing for a crash. The high phaeophytin levels in September and persisting into October indicate that such a crash indeed took place.

September stratification conditions saw little change from August. However, while ammonia levels were high above the thermocline and at the surface in September, chlorophyll levels decreased considerably. Rainfall was high in both October and November, as temperatures decreased. The decrease in temperature, coupled with the heavy rain fall, led to a highly homogenous, well-mixed water column in October, which coincided with some of the highest bottom DO levels of the year. Nitrate and nitrite loading occurred during this time, but the overall DIN levels were low relative to the rest of the year. While the amount of chlorophyll increased from the surface to the bottom, the proportion of phaeophytin was lower at the surface and above the thermocline than at the bottom, indicating growth, photosynthesis, and oxygen production in these areas. November was similar to April—a transitional period of temperature and salinity stratification, although patterns of stratification were becoming less intense rather than intensifying, moving towards the homogenous conditions would later prevail in the winter. This stratification facilitated hypoxic bottom waters observable in Ocean Data

View percent saturation graph. Also observable in this graph is the low-salinity lens creating high levels of stratification, probably a result of the high rainfall. Yet why did October remain homogenous, while November was stratified with freshwater isolated on surface? The reason could involve a warm spell in November observable in the Brunswick temperature graph—perhaps the warm air could have created temperature stratification, which again isolated the bottom waters.

The increased stratification from October to November coincided with a steady increase in both chlorophyll-a levels and nitrate and nitrite levels at the surface. This pattern once again coincides with the findings of Kristiansen et. al. (2001): nitrate and nitrite loading created a period of intense algal growth evidenced by elevated chlorophyll-a levels. A late-fall bloom was therefore in progress.

Water Quality Indicators

While hypoxic conditions persisted into September, the drop in temperature, mixing, and algal production in the euphotic zone that occurred in October resulted in levels throughout the water column falling above the "excellent" DO range of the Health Index (90% saturation) in October. Another indicator of high quality were the low turbidity readings—greater than 3m secchi depth, once again in the excellent range. On the other hand, nutrient and chlorophyll levels remained high: chlorophyll levels were above the 10 ug/L range of the Health Index, and nutrient levels, while low compared with the rest of the year, were still around the 10 uM/L limit of the Index range. This observation points to the importance of stratification in regulating hypoxic events at the lower lake. Without the presence of either a thermocline or halocline, high phytoplankton biomass breaking down at the bottom did not cause eutrophic conditions. In November the salinity stratification reduced mixing, causing hypoxic levels to return, although turbidity and salinity were still low. The hypoxic levels in November were also affected by the late fall bloom apparently brought on by a transition from ammonium to nitrate and nitrite. The phytoplankton at the bottom was indicated by chlorophyll-a and not phaeophytin, however, so the biomass may not have been breaking down. The hypoxia might then be explained by the findings of Kemp et. al. (1992) that phytoplankton respiration can also significantly deplete DO in waters deeper than 5 meters.

Conclusion

Seasonal variations in temperature and rainfall played an important role in regulating patterns of eutrophication at the Lower Lake. One of the major factors influenced by seasonal changes was nutrient loading. Nitrogen levels were central to the observed changes in phytoplankton populations, although the different forms of nitrogen seemed to have different effects. The spring bloom in early March was triggered by nutrient loading, as evidenced by increased nitrates and nitrites. The same was true for the late fall bloom in November. The heavy precipitation around both these times suggests that rainfall may have contributed to nutrient loading through terrestrial runoff and/or atmospheric deposition of nitrogen. However, during the summer, it appears that ammonium being regenerated from the bottom of the deep hole may have maintained the density of the algal population, perpetuating eutrophic conditions through the summer. All in all, the frequently high ammonium levels observed at the bottom of the water column supports Heinig's hypothesis that the deep hole is an important source of nutrient regeneration.

While nutrients undoubtedly played the most important role in regulating algal growth, other factors contributed to the observed eutrophic conditions and water quality patterns. Factors such as turbidity, salinity, and cloud cover seemed to be important in producing the optimum conditions for algal blooms when they occurred, while at other times, they may have contributed to population crashes by increasing stress on phytoplankton. This was apparently true in August, when turbidity and salinity were high.

With dense phytoplankton populations present throughout the year, stratification was central in determining the effects of planktonic growth, respiration, and decomposition on water quality at the Lower Lake. The heavy influence of salinity and temperature stratification is evidenced by the observation that hypoxic conditions only occurred in the presence of a thermocline and/or halocline. The presence of thermal or salinity stratification throughout most of the year may indeed be responsible for the accompanying hypoxic and even anoxic dissolved oxygen levels at the bottom of the deep hole.

These results seem to support the possibility presented by Groves (2002) that the roads involved with the New Meadows River lakes have adversely impacted the ecosystem by restricting tidal flow. Although this study did not examine tidal patterns specifically, the observed patterns in stratification and dissolved oxygen may point to an important conclusion about the influence of tides on the Lower Lake. The effect of tidal patterns on estuarine ecosystems was examined by Demers and Legendre (1981), who determined that vertical mixing of the water column affects chlorophyll levels by changing the light intensity. Thus, bimonthly tidal trends can affect biomass and productivity. Demers and Legendre (1981) found photosynthetic rates, as evidenced by the concentration of chlorophyll per cell, to be much higher in low-flood waters than in high-flood waters, where vertical mixing is intense. They concluded that the intensity of vertical mixing controls productivity and biomass within estuaries.

The work of Demers and Legendre could explain the extent of the impacts of stratification on oxygen depletion at the deep hole. If tidal flow has indeed been restricted, then perhaps the resulting decrease in vertical mixing has unnaturally augmented the effects of stratification, causing eutrophic conditions to persist throughout the spring, summer, and early fall. In the future, it would be interesting to examine tidal patterns specifically, with the goal of creating a model of how tides influence eutrophic conditions at the Lower Lake.

Future studies at the Lower Lake might also focus on building up a water quality index specific to this particular estuary. While the Buzzards Bay Health Index provided baseline standards by which to evaluate the relevant water quality parameters, the conditions upon which the Index was based did not accurately correspond to conditions at the Lower Lake. The fact that most of the parameters at the Lower Lake were off the scale of the point system may be due to differences in depth or other non-environmental factors. However, the Index still provided a useful tool for assessing the seasonal trends in water quality at the lower lake.

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